INVESTIGATING LIGHTNING ARRESTER BEHAVIOUR IN SUBSTATIONS

Thesis submitted for the fulfilment of requirements for the degree of

MASTER OF SCIENCE

in

Electrical Engineering

by

Buyisile Zwe Mzulwini

SCHOOL OF ELECTRICAL, ELECTRONIC and COMPUTER ENGINEERING, HOWARD COLLEGE, UNIVERSITY OF KWAZULU-NATAL, DURBAN - 4041 SOUTH AFRICA.

STUDENT NO.: 212559063

DECEMBER 2020

INVESTIGATING LIGHTNINNG ARRESTER BEHAVIOUR IN SUBSTATIONS

Student:

Buyisile Zwe Mzulwini

Supervisor:

Prof. Akshay Kumar Saha

This thesis submitted in fulfilment of the requirements

for the degree of Master of Science: Electrical Engineering

in

Howard College of Agriculture, Engineering & Science

University of KwaZulu-Natal, Durban

South Africa.

As the candidate's supervisor, I have approved this thesis for submission.

Signed…………………………………….... Date December 2020

Name: Prof. Akshay Kumar Saha

DECLARATION - PLAGIARISM

I, **Buyisile Zwe Mzulwini,** with Student Number **212559063** and the thesis entitled "investigating lightning arrester behaviour in substations" hereby declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research work.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other person's data, pictures, graphs or other information unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other person's writing unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written but the general information attributed to them has been referenced;
    b. Where their exact words have been used, then their writing has been placed inside quotation marks and referenced.

Signed………………… Date: 14 December 2020

Buyisile Zwe Mzulwini

ACKNOWLEDGMENTS

I cannot express enough thanks to everyone who supported and encouraged me in completing this study. I am grateful and thankful.

Firstly, I would like to acknowledge and appreciate my supervisor Professor Akshay Kumar Saha for accepting me to be under his supervision, the guidance and support to be able to complete my research and the School of Engineering in Howard College to accept me to take this journey under their institution, I highly appreciate the opportunity given.

Secondly, I would like to send my genuine appreciation to my beloved and adorable son, Elethu S.A Phoswa for always bringing heaps of joy and putting a smile on my face. I would also humbly express my gratitude to my mother Khethiwe S. Mzulwini for the continuous prayers, support, heart-warmings messages, love and care she is constantly giving me. I would also express my gratitude to my siblings Bazamile Ngidi and Nozipho Mzulwini for their support, Thokozani Phoswa, and my friends Thobeka Ncube, Sharne James, Ntombenhle Mkhwanazi, Mthandeni Magwaza and Linda Takalo for their support.

To conclude, I would like to give all glory to the wonderful God for the strength, wisdom, understanding, most importantly for being my beginning and the end on this journey.

Dedication

This thesis is particularly dedicated to my son, Elethu Sbongakonke Asbonge Phoswa and my mother Khethiwe Scholastic Mzulwini.

God has done this for me.

ABSTRACT

A substation contains switching, protection and control equipment and one or more transformers. This equipment forms a vital part of a substation which facilitates power distribution. The substation provides power for general use by stepping up or down voltage to meet the requirements of the end users. Many challenges are currently being experienced in substations leading to unreliable power delivery to customers. Some of these challenges' ranges from theft, vandalism, safety issues to compliance with regulations. Though all these challenges are worthy of consideration, engineers and researchers often place priority on the safe working condition of lightning arresters because when these fail it may lead to disruption of the power supply. This thesis discusses the challenges of lightning arrester affecting the overall performance of substations. Special attention has been given to the various ways of preventing lightning arrester failure and precautions to be taken in advance. Also captured in this research is the effect of humidity on the life span of lightning arresters. This was studied by conducting laboratory tests and comparing it with the test results. From these results conclusions were drawn. The lightning arresters used for both tests were at a test temperature of 110 ºC for 101 hours and 127 hours for the laboratory. The shape parameter and scale parameter were used to determine the failure rate of an arrester for both field and laboratory condition. It was observed that the failure rate for field and laboratory tests presented shape parameters of 0.31 and 0.30 respectively. The value of 0.31 indicates a slightly larger range of lifetime than 0.30. It was observed that the field test samples showed a higher failure rate than the laboratory test samples. Also, the slope parameters for both cases were observed to be less than one, signifying early-life failures for both tests condition as increases.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	**-Alternating Current**
BIL	**- Basic Insulation Level**
CBM	**- Condition Based Maintenance**
CT	**- Current Transformer**
DC	**- Direct Current**
DFR	**- Digital Fault Recorder**
GLD	**-Ground Lead Disconnector**
HV	**- High Voltage**
IEC	**- International Electro-Technical Commission**
LA	**- Lightning Arrester**
MCOV	**- Maximum Continuous Operating Voltage**
MO	**- Metal Oxide**
MOSA	**- Metal Oxide Surge Arrester**
MOV	**- Metal Oxide Varistor**
MV	**- Medium Voltage**
PCF	**- Percentage Cumulative Failure**
PMFA	**- Public Finance Management Act**
SAWS	**- South African Weather Service**
TOV	**- Temporary Overvoltage**
TEAP	**- Time Equivalent for Aging Process**
UV	**- Ultraviolet**
VT	**- Voltage Transformer**

CHAPTER ONE

INTRODUCTION

1.1 Background

Electric power flows from generation plants to consumers through several transmission and distribution systems. Substations are considered an essential part of the transmission and distribution system as they are used for stepping up and down the voltage level using transformers. Substations typically include primary devices such as current transformers (CTs), voltage transformers (VTs), electrical cables, reactors, circuit breakers, lightning arresters, ground wires and disconnector which are arranged in switchyard or bays [1] [2]. The substation provides various places points for measuring parameters, enabling monitoring, controlling, and securing the geographically widespread power system [3] [4].

Substations equipment is prone to challenges are severe weather conditions such as strong winds, floods, heavy storms, and lightning strikes. These weather con usually cause damages to equipment inside the substation, especially substations located in coastal areas because of high humidity as the air absorbs moisture directly from the sea [5] [6]. Furthermore, a cyber-security attack is reported as one of the challenges due to the high increase in internet and wireless-based usage [7] [8]. In addition to the above challenges, short circuit current related to substation expansion is equally a challenge [9] [10] [11].

The most common challenge in substations is a high voltage surge that can cause harm to insulated equipment inside systems, such as transformers, circuit breakers, reactors, current transformers and voltage transformers. These surges can be prevented or reduced by installing lightning arresters, which take all the surges down to the earth using bonding cables. In addition to this, to ensure that a substation is well protected against surges, proper design, selection, installation, and maintenance must be conducted on a lightning arrester. Furthermore, failure of lightning arrester must be avoided by conducting condition assessment to ensure a safe and reliable substation [1] [3] [14].

1.2 Research Motivation

Reliability constraints is the primary goal of transmission systems. However, conventional and smart substations face many challenges, ranging from theft of installed components, aging, and damages caused by lightning strikes. Over the years, a series of research has been carried out on how these challenges can be minimized to give consumers maximum satisfaction. Substation operation has many challenges the electricity provider's tend to experience which are the effect of damages caused by lightning strikes in substations and the negative impact of humidity on the aging process of lightning arresters due to moisture ingress that has accumulated into the arrester's internal region [15] [16].

To avoid these damages, each piece of an electrical component in an electrical power system needs to be protected from voltage surges (external overvoltage or transient voltages) to prevent damage to the systems that work at a specific voltage range. When these devices receive a voltage way higher than the rated voltage sufficient for their operation, they tend to blow up or get damaged. However, an electrical system protected by a lightning arrester does not get damaged, the arrester ensures that the high voltage does not enter the electrical system [17] [18] [19].

Therefore, surge protection is considered to be essential and critical to a well-designed electrical system. Shifting the focus to the protection of substations (high-voltages/medium-voltages - (HV/MV)), the reliability of operation against atmospheric overvoltage (the most dangerous overvoltages induced primarily by thunderstorms with lightning discharge) is a critical aspect of any electric components. Therefore, improvement of lightning arrester performance is a technical issue of great importance related to the safe, uninterrupted high-quality power supply [3] [20]. Substation protection design of overvoltage equipment involves an accurate determination and selection of the protective device [18] [21]. The selection of a reliable protection system is an important decision due to its significant monetary investment and reliable operation [22].

However, there is a very high probability that these arresters may fail to protect the installed electrical components within the substation. These failures may be as a result of improper maintenance and condition monitoring of the lightning arresters. Even though frequent maintenance monitoring is carried out, there has been a high number of lightning arrester failures over the years, which has made it difficult for entities to provide their customers with a reliable service [23] [24] [25]. Further investigation through testing was required to determine what could have been the cause of such an increase in the number of lightning arrester failures. Samples of failed arresters that had burnt off and have been removed from service were bought into a testing laboratory designed to accommodate testing of lightning arrester and other electrical equipments, and results indicated that:

1. If an arrester had failed due to an excessive surge or power follow-on current, the value of leakage current increased. Spark gaps (gapped arresters) may have been damaged.
2. Condensation, moisture ingress, and partial breakdown of oil can result in corrosion or even contamination of the spark electrode surface if experienced by the arrester's internal insulation several times.
3. A power frequency leakage current test can be utilized to detect any severe internal damages on the arrester, so this test is conducted by choosing a voltage below but closer to one of the arrester ratings [26] [27].

The majority of arresters are installed in fields to protect outdoor equipment. porTable field tests are required as part of the condition monitoring systems to check the arrester's operating condition [21, 27]. Conventionally, it has been an adopted culture that they are taken into a laboratory to test and investigate root causes and effects when arresters fail. The results from these investigations of failures have indicated that these failures could have been mitigated at an earlier stage, and failure could have been avoided. Therefore, premature lightning arrester failures or damages on the field can be prevented, and this can be done by conducting tests which can view symptoms indicating early detection of the damage by the utilization of two porTable field tests; impulse flashover field test and power frequency leakage current test [27] [28].

Lightning arrester failure can be due to many factors such as excess of surge current, thermal condition, temporally rise on overvoltage, moisture, ingress, deterioration due to contamination, freeze or thaw process, air pumping, low quality sealing that can deteriorate gasket material, corrosion, aging of insulation material, improper installation and many more other factors not being mentioned. However, lightning surges have been the root cause of failure [19] [20] [28].

Furthermore, when a lightning arrester has been installed, humidity rises due to pollution caused by salt, dusts and gases that harms the degradation of metal oxide high-voltage surge arresters installed in substations. Humidity is a factor determining a lightning arrester's aging process wherein cases of under operating voltage can cause an increase in the varistor current. This occurrence is likely to cause the metal oxide arrester to fail completely. In the field, the humidity can lead to internal discharges due to moisture ingression into the arrester's internal region. This moisture ingression is an essential degrading external factor that needs to be monitored carefully after years of operation [29] [30].

1.3 Research aim

A voltage surge in a substation results from external or internal surges such as lightning or switching and temporary overvoltage. The surges can harm expensive and critical pieces of equipment; if not adequately protected, they can further cause explosion and safety problems. For surge protection, lightning arresters have been used in substations for over a decade in South Africa, Australia, Nigeria and other countries, which has led the researcher to look into how best lightning arresters can be maintained to save substation components from being damaged from the after effect of surges lightning strikes or switching. The researcher has also provided a concrete understanding of how lightning arrester can be selected and maintained to accommodate the substation's components' strength and ratings.

1.4 Research problem statement

Substation play important role in the power supply system; hence they need to be protected and well sustained for power availability. However, substations are faced with lots of challenges ranging from cybersecurity, theft and fault current. All these challenges have a negative impact on the performance of substation. Additionally, one of the challenges substation experiences is the rise in voltage surges due to high number of lightning being experienced in the area where the substations are situated, which is in Piet Retief-Vryheid (Mpumalanga) in South Africa, and is ranked between 9-14 flashes/km squared per annum shown on (Fig.2.2).

1.5 Research methodology

For this study, research questionnaires focusing on covering an overview of lightning arrester's performance were identified and discussed. Information to build up these questionnaires collected on the field from experienced different groups of employees working for different companies based here in South Africa and were summarized into three, discussed was details is how companies select, install and maintain lightning arresters. this type of research method was selected because it's a good way obtaining information from a group of people without having to directly interview them and allowing the participants to state their views without any possible reaction of the researcher. Also, covered in this report is the analysis of lightning arrester behavior staged into two different processes. The first process was when a lightning arrester is subjected into high temperatures on the field and the second was when a lightning arresters is tested at the laboratory.

Filed test process: During this process, questionnaires to experienced people on the field was conducted and results were handed over that were captured on the logbook that is kept in a substation, those results were then analyzed and compared to the laboratory results.

Laboratory test process: During this process lightning arresters were taken into the laboratory in Johannesburg, South Africa where maximum temperature of 110°C was induced to it insulation.

1.6 Research questions

This research paper aims to understand how different utilities protect their substation against surges and what procedures they follow to ensure that insulated components are protected against surges. The questions below were developed by the researcher to gain factual knowledge and understanding of the subject matter.

1. What is the installation procedure used for lightning arresters, the type being installed, and benefits?
2. What maintenance and testing procedures are carried out on lightning arresters?
3. What are the selection criteria used to select lightning arresters suiTable for substation equipment protection? [28] [31].

1.7 Research hypotheses

The hypotheses based on the research questions stated above are as follows:

1. Arresters installed on closer to the components to be protect are more secured from the effect of surges entering the substation uninvited.
2. Conducting condition assessment is one of the most critical aspect that can lead on what needs to be maintained before lightning arrester failure. To inspect connections, cracks, carbon black spots, clearance and alignment is one of the ways to maintain an arrester, keeping it in a good condition.
3. Coordination with the basic insulation level of the equipment to be protected can be achieved

1.8 Structure of the research

This study is structured as follow:

Chapter one: introduces the topic by discussing the topic's background and what to expect in the report.

Chapter two: presents a literature review of the different types of surges that attack the substation and how lightning arresters protect these systems against these surges. It further discusses the installation procedure, types, and selection criteria used when selecting a lightning arrester. It also elaborates on the challenges that affect the performance of lightning arresters. It gives an overview of the importance of having a lightning arrester as protection equipment in a substation.

Chapter three: This chapter discusses the research aim and objectives guided by the researcher's research questions to gain knowledge and understanding of lightning arresters. The information noted was taken from the specialist who has been working in the field for years on the 29th of May 2020 in Vryheid, South Africa.

Chapter four: This chapter presents an analysis of the influence of under polluted contaminations on the degradation of metal oxide high-voltage surge arresters used in substations. It gives detailed information on the adverse effects of moisture ingression into the arrester's internal region. Important parameters have been calculated, analyzed, and captured in this chapter.

Chapter five: presents the study's findings and discusses the results of field findings related to lightning arrester usage and testing; it also gives a brief analysis of chapter three findings.

Chapter six: summaries and concludes the research by providing conclusive insights into the study and outlining salient recommendations for future studies regarding this topic.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The occurrence of lightning has been revealed as one of the significant causes of loss of service in both the transmission and distribution networks. Thus there is an increase of over 70% in demand for overvoltage protection equipment in South Africa against lightning occurrence in power systems due to the rate of failure of the currently installed arresters [4] [17] [19]. Also, lightning is one of the sources of surges in an overhead lines and to other substation equipment. It is a powerful sudden electrostatic discharge accompanied by thunder during a thunderstorm [5]. Lightning strikes, however, are not the only cause of severe network voltage surges. Other sources may also lead to transient voltage surges, such as surge voltages associated with switching capacitors [3], surge voltages due to the equipment insulation's failure, resulting in a short circuit on the distribution network, surge voltages associated with the lightning arrester discharge at the other location inside the facility [17] [27].

Substations may be defined as a combination of devices providing switching facilities that convert electrical energy from one shape or level to another shape, with lightning arrester devices that helps prevent the apparatus from being harmed due to high voltages [10]. Lightning arresters provide path to the current resulting from lightning stroke or transient voltages with a low impedance path to the ground and then returned to normal operating conditions [11]. Also, arresters are primarily used to protect significant equipment like transformers, rotating machines, shunt reactors, and even the entire substation [13] [14].

2.2 Lightning arrester overview

Lightning arresters are a shielding device that carries out surges down to the ground; they shield electrical devices from direct or indirect strikes by using the electrical triggering device to allow passage of surges resulting from strikes. Direct strikes are lightning discharge from the cloud to the line's subject equipment; the current path may be over the insulator down to the ground. However, indirect strikes originate from the conductors' electro-statically induced charges due to cloud presence. The sensor enables the ground mat and earth spikes to accept and surges being experienced by an arrester to earth or ground. The housing of an arrester can be either porcelain housing or vandal proofed housing.

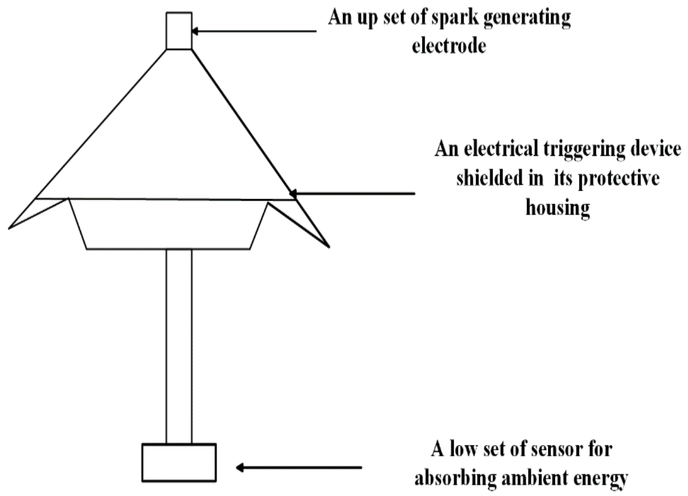

Figure 2. 1 Lightning arrester diagram [28].

Furthermore, different terms are used interchangeably for lightning arresters by professional engineers and electricians, but they do not mean the same thing in practice. Such terms are Surge suppressor, Surge arrester, and lightning rod [31] [32].

2.2.1 Surge arresters

The surge arrester is a device used to shield electrical installations and other components from electrical surges and transient voltages triggered by electrical faults, switches, short circuits, sparks and lightning. Inside the panels, surge arresters are mounted in tap-off configuration between live and earth conductors to suppress the surges [33] [34]. The most popular surge arrester is a nonlinear metal oxide (ZnO-based resistor and silicon carbide type) in a porcelain or silicone rubber housing and is installed in parallel to the designed circuit to protect it from surges and connected to the earth grid [35] [36].

2.2.2 Surge Suppressor

Surge suppressor also known as a transient suppressor, a surge protector is mounted on the home panel board to protect the electrical surges and voltage spikes known as transients from connected circuits. The difference between surge suppressor and lightning arrester is that a surge suppressor has low voltage rating with low energy dissipation capability while lightning arrester has high voltage ratings than the rated voltage with greater energy dissipation ability without affecting the insulation [26] [34].

2.2.3 Lightning Rod

A lightning rod is a metal rod mounted on top of the iron bar device or a building to protect it from direct lightning strikes (copper or aluminum, or other conducting materials). When lightning strikes the voltage will rise to a dangerous level of electrostatic discharge between clouds and earth reach power lines directly, potentially damaging the electrical installation and equipment [35] [36]. A lightning rod is therefore used to shield electrical systems or machines in side buildings from the direct impact of lightning strokes [37].

2.3 Surge arrester versus lightning arrester

The most commonly used term in place of the lightning arrester is the surge arrester, which differs from the lightning arrester in the following ways. Inside the panel board, surge arresters are mounted, while lightning arresters are mounted outside the panel board. The surge arrester protects the equipment from the inside panel room, while the lightning arrester protects the equipment inside the substation as a whole [34]. The surge arrester is commonly used to protects equipments against lightning, switching surges, electrical and other errors such as transient voltage and surges from damaging the devices on a system, whereas the lightning arrester is primarily used for lightning strikes and any other surges, it ability of protection against any other surges is not the main reason why most companies install lightning arrester on their substation but lightning is [35] [37]. The surge arrester intercepts the spikes and transfers the unnecessary extra energy to the ground wire while the lightning arrester diverts the surge of energy to the ground through the arrester, also, lightning arrester cannot be used as a surge arrester [37] [38].

2.4 Lightning arrester principle and function

A lightning arrester is device on electrical power or telecommunication system which, when the system detects a huge voltage spike, diverts power to the ground. Such devices are designed to operate somewhere down the line with a direct lightning strike or an intense surge from a fault. At each substation, multiple lightning arresters are needed as each transformer and piece of switching equipment such as disconnector and bus bars needs to be secured. There are many kinds of arresters for lightning, such as forms of expulsion and valves. Note that large substation circuit breakers and lightning arresters look similar; both are tall ceramic tubes [26] [28].

Lightning arrester connection has one of its side connected to live (line) and the other to side to earth ground. This enables the line to ground faults to be discharged to the ground when an arrester experiences high or excessive overvoltage. When an arrester experiences surge voltages, surge current is discharged immediately to the ground terminals on an excellent condition arrester. Hence, substations must be well-grounded, with a ground system of equipment connected together using ground wires for proper surge discharge [39] [40].

The primary role of a surge arrester/lightning arrester has remained unchanged. Lightning arresters help prevents system damage due to high voltages; this is enabled by creating a low path impedance to the ground for lightning strike current or any other transient voltages and restores it to its usual working conditions. Surge currents are discharged to the grounding terminal when lightning discharges through an arrester. The safety of substations and overhead with well-grounded bonded wires are very crucial for safety purposes of employees or visitors. It is also important to bond the ground system between pieces of equipment. [17] [32] [33].

2.5 The importance of a ground lead disconnector and ground lead on an arrester.

2.5.1 Ground lead disconnector

A disconnecting device must be provided following IEC 60099-4 in case the lightning arrester fails, and the ground lead disconnector must be able to disconnect from the earth tail in order to isolate the arrester electrically from the system and to give a visible indication of the failure that may have occurred [18].

The GLD external housing must be UV sTable, and precautions must be taken to ensure that it does not deteriorate in service as a result of being exposed to the environment, permanently sealed to prevent moisture ingress, and its full operation is only required once an arrester has failed. An arrester's withstanding capability must correlate with the withstanding capability of its GLD for proper isolation of an arrester with causing any further damages on it when it has failed and is required to be changed and for a new one to be installed easily on the same point where the removed arrester was installed [23].

2.5.2 Ground lead

Arresters must be supplied with flexible ground leads attached to the earth terminal. In most cases, the braided types of ground leads are preferred. The GL must be flexible in such a way that it allows the GLD to operate correctly and can be able to isolate the arrester permanently from the ground [32].

2.6 Lightning arrester selection procedures

The appropriate selection and application of an arrester requires accurate and precise decisions. When selecting a lightning arrester, the aim is to select an arrester with the lower ratings for proper and reliable overall protection of the equipment insulation and power system in protection. Selecting an arrester with higher ratings has high chances of allowing surges to pass through the equipments that needs to be protected without causing any damages [41] [42].

The proper selection and application of an arrester on a system are based on:

2.6.1 Selection of lightning arrester voltage ratings

This requires proper selection the grounding system for both high grounded resistance (mostly used found in low voltage system, meaning certain resistance has been internationally put between neutral and ground) and low ground resistance (normally found on medium or high voltage systems to limit ground return current to a high level) of where an arrester will be installed. This means considering the full continuous path to ground voltages that can occur at any given time and determining the ratings that are not expected to be surpassed. In short, the arrester rating depends on the manner of the system ground [41] [42]. The peak continuous operating voltage rating of the selected arrester must be greater than or equal to the maximum condition voltage which varies depending on the ratings of an arrester in question.

2.6.2 Selection of lightning arrester class

The class of lightning arresters to be considered depends on the value and the importance of the secured equipment. There are four different types of classes.

Station class - This type of arresters is commonly used to protect against high line switching overvoltage and high fault currents. It is usually used by utilities owning substations, electrical power stations, and any other high voltage systems. Hence, the reason it ranges of protection is equipment above 20 MVA ratings and can be used for ratings below five MVA.

Intermediate class - This type of is intended to provide complete protection for power in the medium voltage class systems such as substations, transformers, Virtual Retinal Display (VRD) cables, and any other substation equipment. It is designed to protect equipment ranging strictly between 1 MVA to 20 MVA.

Distribution class - Mostly found on transformers (dry-type and liquid-filled type) with rating ranging from the upper limits of 1000 kVA or less, also it found exposed line having direct connect rotating machines.

Secondary class - Planned to shield residences and companies against lightning strikes and electrical power supply companies, ranges from 380 V or less [42] [43].

Selection of physical location for an arrester to be installed - On the location selected, lightning arresters must be installed directly at the terminals of the equipment it is protecting; the location should be adequately grounded and so that the arrester enables surge voltages to be discharged through it instead of the equipment being protected [44].

To ensure proper protection of substation against lightning surges, a high insulation level is required, proper installation of earth mat and additional earth spikes if required, especially for places with high soil resistivity. The following parameters should be considered when designing an arrester; the lightning strike's location, the geometric features of the external lightning defense device, the grounding resistance, and the basic insulation level (BIL) are all parameters that affect the lightning impact strength. When installing an arrester, it must be close as possible to the transformer to protect it [44] [45].

2.7 Causes of lightning arrester failure

The capacitors in a circuit can be easily interrupted by unsTable voltages when a circuit switches on and off, causing restrike to disturb the capacitor circuit current. Resulting from the restrike might be a steep front voltage execution that may be high enough to cause damages on a rotating machine applied at the same voltage [41] [42].

Restrike can cause a voltage surge to a neutral crest value over three times the standard line. The wave-front severity and steepness are not as extreme as that of lightning strikes, which can cause damages. Alternatively, weaken the winding of other equipment that does not have a higher basic impulse insulation level rating. [43].

2.8 Lightning arrester and ratings selection.

Under regular operation in a substation, the lightning arrester is continuously exposed and continually experiencing power system operating voltages. This is why it is critical that for every arrester rating, a suggested limit to the voltage magnitude that can be continuously applied on it be known, and this voltage is called maximum continuous operating voltage (MCOV) [41] [42] [43].

Temporary overvoltage (TOV) - TOV ratings should be considered during the selection procedure. TOVs results from numerous events such as switching, line to ground faults, load rejection, loss of neutral, and Ferro resonance, but mostly temporary overvoltage are caused by earth faults. Reduction from earth faults can be obtained by effective earthling of the neutral and ensuring it is done correctly and not loose. Effectiveness of earthling is assured when the system is appropriately and well-grounded, meaning all structures, terminals, and earth wires are connected to the system's earth mat [45] [46].

Basic level insulation (BIL) - lightning arresters are chosen in accordance with typical overvoltage electrical equipment isolation. This arrangement is based on an arrester's option that discharges at a lower voltage level than the voltage needed to crack the insulation [47].

2.9 Lightning arrester advantages and disadvantages

An arrester can behave both like an insulator or a conductor, depending on the amount of current it is experiencing. For instance, when a small amount of current with power frequency voltages ranging between 50 Hz to 60 Hz, it will behave like a conductor. However, when a large amount of current with frequency voltages between the ranges (KHz-MHz) is injected into it, it becomes highly conductive, enabling an arrester to consume current and transfer high energy to the ground overcurrent. [48] [49]. During this process, the good thing is that the across its terminals, voltage decreases low enough to shield the insulation of equipment present in the power system from overvoltage and high energy overcurrent [39].

Lightning arresters are also best known for their excellent performance when it comes to lightning protection they detect presence of electrostatic in the atmosphere [22] [31]. A damaged arrester that is not detected at an early stage and not removed on the substation may lead to power outages at some of overcurrent may disturb the operation of circuit breakers and relays that may lead to tripping of the entire system while not causing any further harm to the power system [32] [37].

Moreover, the majority of lightning arresters are designed with a cooling system of 60 degrees Celsius after experiencing heat from high lightning surges, and the cooling period for it to be able to handle the next high surge current which usually takes up to an hour (60 s – 74 s). With such a high cooling period, lightning surges can occur at any time, leading to explosions as the transformer will be unprotected and experience high current surges. Additionally, the prolonging of high energy exposure on an arrester may lead to explosion [33] [36].

2.10 Lightning arrester types

Lightning arresters are typically categorized into various groups. The design of lightning arresters differs according to their form, but the operating principle remains unchanged. This provides a low path of resistance to ground for the surges. The following are the types:

1. Rod-gap arresters
2. Sphere gap lightning arresters
3. Horn gap arresters
4. Multi gap arresters
5. Impulse protective gap arresters
6. Spike Rod arresters

7. Valve type of lightning arresters
8. Pellet lightning arresters
9. Metal oxide lightning arresters
10. Line arresters

    [50] [51].

2.10.1 Horn Gap Arresters

In a horn-shaped type, this arrester has two metal rods, as the name suggests These metal rods may technically be installed around a small air gap to position these metal rods. The distance between these two rods can also be increased as they extend from the gap. On ceramic isolators, the metal rods are located. By connecting it to two separate wires, the horn connection can be made. The other side of the horn can be connected through resistance and choke coil to the line, while the second part is efficiently grounded. The resistance restricts the movement of the present to a minute value. At the standard power frequency, the choke coil provides less reactance and provides high transient frequency reactance. Therefore, the choke coil does not allow the transients in the apparatus to be secured. It is possible to adjust the distance between the horns so that the average supply voltage is not enough to trigger an arc [18] [27].

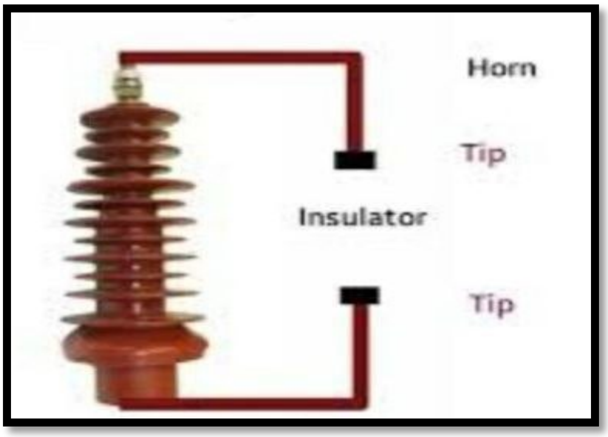

Figure 2. 2: Horn gap type of arrester [46]

2.10.2 Multi Gap Arresters

These arresters are designed with a series of metal cylinders isolated through air gaps and disconnected from each other. The main cylinder is linked to the electrical grid in the cylinder sequence, while the remaining cylinders are connected to the field by a series of resistors. There is a shunt resistance between each of the lengths between the next cylinders that detects a surge when there is a surplus voltage [44] [47].

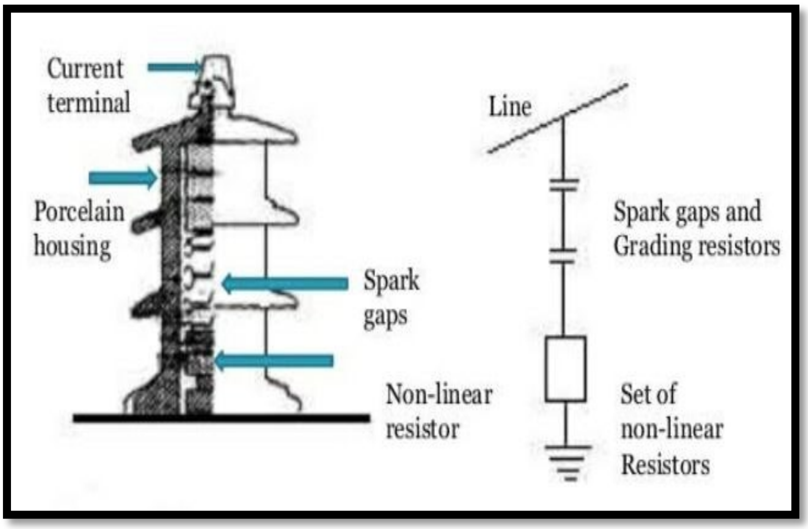

Figure 2. 3: Multi gap type of arrester [48]

2.10.3 Valve-Type Arresters

For electrical systems that are high-powered, these types of arresters apply. Two key components, such as a sequence of spark gaps and a series of nonlinear resistor disks, are used in these devices [9]. Whenever an intense voltage causes the spark gaps to stroke and the nonlinear resisters keep the voltage inside, these devices' work can be completed, whenever the surge of surplus power stops, the resistors can push the spark gaps separately [48] [51].

2.10.4 Pellet-Type of lightning arresters

Glass tubes that are loaded with lead pellets can be used to design these arresters. These are completed by coating lead oxide from the inside of the lead peroxide. Lead oxide is not powerfully conductive inside the lead peroxide. It transforms into lead peroxide until the lead oxide is heated up and provides the current flow. Whenever the current flow is transmitted, the lead peroxide will transition to lead oxide in reverse. This form of an arrester is not regularly used [46].

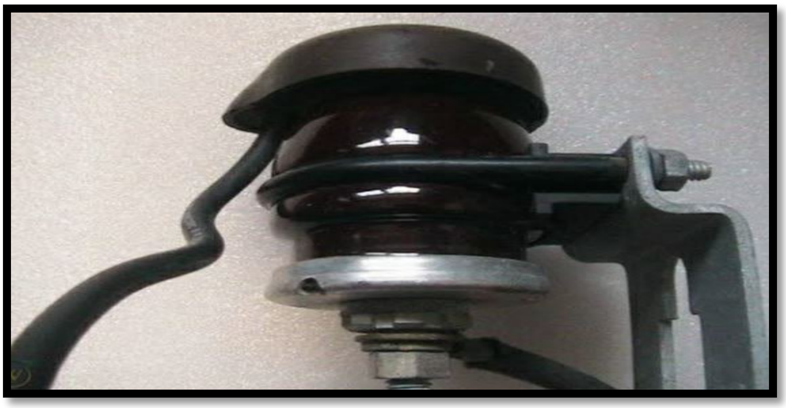

Figure 2. 4: Pellet type of arrester [51]

2.10.5 The metal oxide varistor (MOV)

This type of arrester is a nonlinear system resistance, with voltage that can rise to a very high exponent by the current through the MOV. The MOV conducts only a tiny current under typical operating voltages, in the order of micro-amps. This current has no significance for the device, but because of this current, it has significance for the arrester, causing heating. The maximum continuous operating voltage is one of the leading rating parameters of an arrester, and this refers to the permitted steady-state increase in temperature of the arrester [36] [40] [49].

2.10.6 Metal oxide surge arresters (MOSA)

MOSAs are typically used to protect a power system's insulation or part of it from excessive stress due to overvoltage. In terms of heat, metal oxide elements are capable of dissipating energy from transient over-voltage. For lightning arresters, there are plenty of designs in place. For insulation coordination, arrester position, and energy absorption studies, adequate modeling of their dynamic characteristics is crucial. In addition, these arresters on several devices are replacing silicon carbide arresters [36] [50].

2.10.7 The Metal Oxide (MO) lightning arresters

MO surge arrester also provides shunt-capacitor banks with greater security than were affordable. A shunt-capacitor bank is a high-energy storage system that, when the arrester runs, discharges energy through the surge arrester. When air-break switches are used, MO surge arresters display superior efficiency. Silicon-carbide-gapped silicon carbide-gapped arresters are considered to fail due to various air-break switch restrictions. They are often dependent devices, too. In other words, the voltage around the arrester is a function of the increasing rate and the magnitude of the arrester's current. [31] [41].

If any, the MO arresters perform a little; power follows current and can tolerate continuous spark over’s with far less risk of damage. In polluted areas, the accumulation of pollutants on the surge arrester's housing can cause voltage imbalances on the gap structure of the silicon-carbide surge arrester. If this imbalance becomes too significant, a breakdown of the gap circuit may occur, leading to the arrester's failure. [36].

2.10.8 Transmission line surge arrester

Transmission line surge arresters are installed or found on protected lines where the resistance of the tower footing is high, and mostly the area being prone to lightning and lower footing resistance are not practical [41] [44].

1. Non-gapped line arresters

This type of line arresters offer a high degree of mounting flexibility and operational reliability. In addition to this, due to their high absorption capacity, they provide a very high degree of defense against lightning-induced surges and network generated switching impulses current overvoltage [49] [50].

2. External gapped arresters

This type of line arresters has a spark gap with a galvanic material that isolates the active part of the arrester from the voltage of the line under normal conditions. The sparks that rises in the event of lightning, and the surge is safely discharged to the ground. EGLA prevents all insulator flashover caused by lightning strikes. As such, EGLA increases network stability as well as the availability of the overhead line. Additional benefits of EGLA is that there is no leakage current because the series gap disconnects the active part of the EGLA from system voltage [37] [51] [52].

2.11 Lightning arrester maintenance and condition based maintenance

Maintenance and testing are crucial and must be managed for lightning safety systems. For all lightning protection systems, the inspection and maintenance routine should therefore also be identified. The extent of maintenance work to be done relies on the following:

1. Weather-related quality loss and environmental factors.

2. Impact of a direct lightning strike that leads to potential damage [21] [23].

It is necessary to schedule a maintenance routine; this enhances the comparison between the current and earlier maintenance results. For later inspection, these values may also be used for comparison. The following steps should be included in the routine maintenance of all conductors and components of lightning protection systems.

1. Measuring the consistency of lightning protection system installations.
2. The earth resistance test of earth termination system.
3. Visual examination of all surge protection systems to detect if they have been compromised or triggered.
4. Repair circuits and conductors.

After additional installation or alteration of the structure, inspection to assess the lightning defense system's efficacy remains unchanged [53] [54] [55].

Condition-based maintenance - with new technology's exponential growth, maintenance in many industries plays a more critical role. Reliability and maintenance are some of the most important problems in some sectors, such as the electric power industry, because a tiny failure can lead to immeasurable damage, even a fatal catastrophe. Researchers have been paying closer attention to maintenance and reliability studies in recent decades. Maintenance is characterized as all activities intended to maintain or restore an item to the physical state deemed appropriate for the performance of its manufacturing function [1] [2] [7]. Breakdown maintenance, also called corrective maintenance, reactive maintenance, and unplanned maintenance, is the standard type of maintenance. It is restricted to failure-induced repair behavior or object replacement. Early maintenance is primarily reactive, as it only responds to faults or failures. Time-based preventive maintenance is a newer maintenance strategy (also called planned maintenance). Instead of only responding to failures, constructive maintenance sets plan to inspect or conduct preventive maintenance [56] [57].

.

A preventive replacement system based on a constant interval is a time-based preventive maintenance process in which defect replacements are performed instant after failures occur, and preventive replacements are performed regularly. The age-based substitution process, in which replacements preventative measures are carried out when the part reaches a prespecified age, is another time-based preventive maintenance method, and the challenge of optimization is finding the optimum preventive replacement age. Compared to early maintenance methods, the time-based maintenance approach is advancement; however, it also enhances and increases the cost of preventive maintenance. Preventive maintenance costs have ultimately become for many utilities, a heavy financial pressure. More reliable maintenance techniques, such as condition-based maintenance (CBM), are also being implemented to overcome high preventive maintenance costs and avoid unexpected failures at the same time [58] [59].

The CBM is a maintenance process that uses the information collected from condition monitoring to determine maintenance actions. It is based on the awareness that a piece of machinery [5]. CBM tries to prevent needless maintenance activities Only when there is evidence that the failure is approaching through performing maintenance steps. CBM has been widely used in many areas, including the aerospace industry, the coal industry, the oil industry, and the power generation industry. In order to make maintenance choices, CBM will use data obtained from substation condition tracking, electrical analysis, mechanical analysis, environmental conditions. The electrical analysis is made up of leakage current, partial discharge, waveform analysis of substation equipment such as transformers, circuit breakers, lightning arresters, etc. In the CBM process, there are three essential steps: data collection, data processing, and decision-making for maintenance, as shown in Figure 1. The phase of data collection is to collect data related to system health information. Processing and analyzing the acquired data is the data processing stage. Successful maintenance policies will be collected based on the evaluated data in the maintenance decision-making process [1] [19] [24].

2.12 The most common lightning arrester failures

A damaged lightning arrester will lose its characteristics as an insulator under power frequency conditions allowing current to flow through it. However, some damaged arresters cannot allow the flow of current after occurrence of short circuit or fault tripping depending on the nature of failure at that instant. Moreover, sustained high energy exposure on an arrester may further harm it, resulting in an explosion. [32] [33] [35].

Failure of an arrester can be due to various reasons, and different companies in Shanghai, China and South Africa are experiencing a large number of failures; studies have shown that moisture ingress can be the root cause of some lightning arrester failures. This was proven by a cross-functional/executive team formed to do fault finding or root cause analysis for nineteen arresters that had failed in Tennessee in the USA. The team had compared information from both digital fault recorder (DFR) which was installed on lightning arrester to record every event and physical evidence from the arresters itself; the DFR had shown that arresters had flashed over the internal cavity. But based on physical information that was obtained from available arresters, it had shown that moisture ingress was likely the cause of these lightning arrester failure, and therefore it was concluded that the failure was due to improper sealing of arresters during unit manufacturing [48] [49].

Different types of lightning arresters are designed with a removable tail disconnector for instances when an arrester is damaged or had failed, an arrester can be disconnected from the system. Some arresters are designed with tails disconnector that are not removable and in a case of a damage arrester, it can cause fake transient, consequently tripping the protection system. However, there are scenarios where the disconnector tail fails to function as expected, and with such results, it becomes difficult to detect failed arresters installed on the system [35] [43].

Some companies were experiencing a significant number of lightning arrester failures. Upon investigation, it was discovered that it was due to a change of transformer configuration initially connected 'line to neutral' and changed into 'line to line' to reduce and eliminate interferences from the antenna that provides signals from. The line to line configuration on the transformer was susceptible to Ferro resonance overvoltage; this was concluded by analyzing the type of lines used that had enough shunting capacitors to cause damages to the system. It was further discussed that when one phase becomes open, an overvoltage rise was experienced, resulting in a blow of fuses and single-phase breakers [38] [39].

An arrester experience surges when a rise from lightning or switching transient is induced on it. A lightning stroke carries a high voltage, and when directed to an overhead line, it can cause overvoltage just by one direct stroke or even worse, since lightning, by raising the ground potential of that power system in place always chooses a path with a lower impedance, in this case, it becomes impossible with the high ground impedance taking place.

If not limited by insulation flashovers, the light voltages induced by a direct strike may be as much as 1 MV or greater. [3] [4] [38].

Apart from direct surge, there is a different form of surge called an induced surge. Lightning does not hit the relevant electrical system; however, during the lightning discharge process on the clouds, a surge is formed. A bond of charges is released, rapidly neutralize with charges on the sphere- forming a lightning channel that can strike away from the electricity system to a point [4] [28]. from the ground. And effect of high flash density in an area can cause or lead to lightning striking in one point repeatedly.

South African weather service (SAWS) on 2005 installed lightning detection sensors that will detect the lightning stroke's time and location in real-time using the state-of-the-art magnetic direction finding and time of arrival methods. Substations with to high flash density are more prone to lightning; hence, they require attention and powerful protection against it [11] [13]. Table 2.1 categories the different ground flash densities.

Table 2. 1: Ground flash density categories [11]

Ground lashes/km^2/annum	Categories
0-3	Very low ground flash density
3-6	Low ground flash density
6-9	Average ground flash density
9-10	High ground flash density
10-12	Very high ground flash density
12-14	Extremely high ground flash density

Fig.2.2 below shows the effect of flash density around South Africa. The provinces which are mostly affected are Mpumalanga, KwaZulu-Natal, and Free State. The substations around these provinces need more attention and protection against lightning surges as the flash density is high and can cause safety issues and damages to insulated equipment inside the substation. Installation of lightning arresters can have a significant impact in protecting this critical insulated equipment.

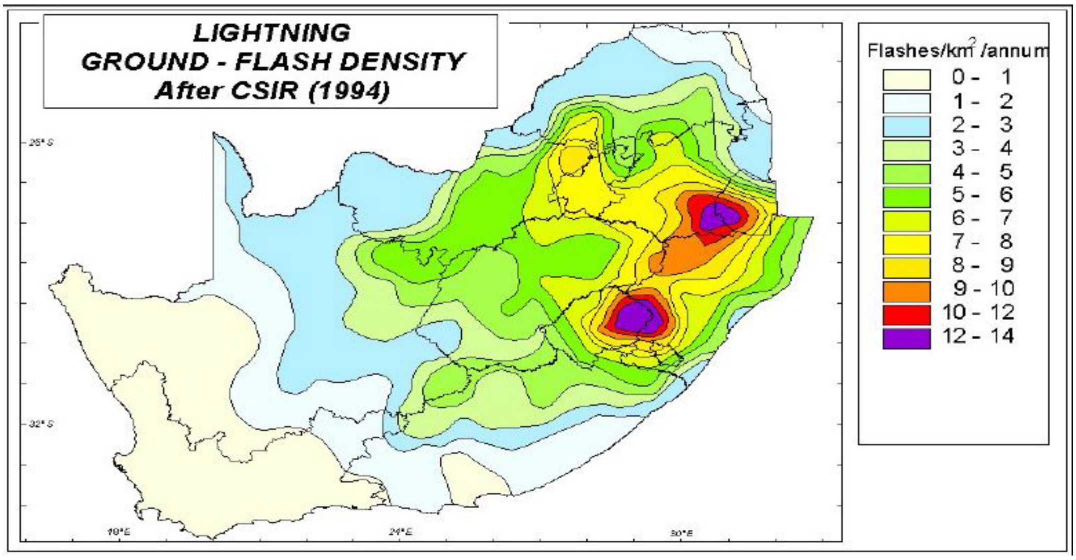

Figure 2. 5: Flash density [11]

According to the International Standard's basic guidelines ISO 14 000 environmental management, installation of a protection system for any environmental changes assures limited contribution of overvoltage produced and reducing the expected lightning defects. The specification of a device for lightning protection has to consider the stochastic existence of external overvoltage phenomena and a substation's various techno-economic influences and constraints. The location of the lightning strike, the geometric properties of the external lightning defense system, the grounding resistance, and the basic insulation level (BIL) are parameters that affect the intensity of the lightning impact.

Moreover, whether or not surge arresters are installed at different substation positions. It has a decisive impact on the magnitude of the overvoltage produced and, consequently, on the expected outage rate. [9] [10]. The safety of substations against the deleterious effects of lightning can be accomplished using the highest levels of insulation, taking account of the financial expense, or installing overhead ground cables to intercept lightning flashes [11] [13]. Implementation of gapless surge arresters with metal oxide can also improve the installation's lightning efficiency, especially in regions with high soil resistivity

2.13 Placement of lightning arrester

The most vulnerable point is always the transformer or reactor HV windings. You therefore try and protect the vulnerable point. Therefore, the placement of surge arresters depends on the needs of the equipment. The basic rule for the placement of surge arresters is to locate them as close as possible to the equipment to be protected. In a substation line, feeder equipment is protected by surge arresters placed at the substation and causing damage to equipment. Substations have overhead screening as well as lightning arresters. Equipment situated in substations is also protected by overhead earth wires fitted to the substation steel structures' tops. This is referred to as screening, and the purpose is to conduct lightning strikes away from the substation equipment and down to earth.

Generally, lightning arresters absorbs and accumulates energy from the various electric fields and, by triggering the charge from the top tip of the arrester, eventually ionizes the ambient air. An upward leader comes into being with the increase the ion's strength, encountering the downward leader of the storm cloud. Some lightning arresters are nonlinear and some are gapless types of arresters. By adding these resistors and series gaps, the different ratings of arresters are constructed. The number of resistor-gap modules is a function of each and the desired final rating's incremental voltage rating. On the smallest module intended to be used in the final design, all of the necessary design work on lightning arresters is completed.

The designer must, therefore, make certain assumptions about the module voltage rating at the outset. A compromise based on dimensional and economic factors is this presumed or desirable module voltage rating. The resistor must usually be of a given diameter, and its height is a function of the thermal requirements imposed upon it by the different application conditions. At defined currents, the resulting protective or discharge voltages then decide if the basic design is correct.

On the other hand, at an assumed module voltage ratings of an arrester gap are supposed to work correctly. The amount of current it must interrupt is calculated, in part, by the characteristics of the resistor just discussed, and also by the features of the gap in a current-limiting gap arrester. If it is found that the gap is not capable of clearing a sufficient margin of the fault current permitted by the arrester, then it would be necessary to decrease the combination's voltage level, which would, of course, increase the number of modules used in the final design for a given voltage rating.

Lightning is destructive in nature. Often when not properly secured, it results in insulation failure, shattering of insulators, or burnout of power equipment, particularly in outdoor substations. Its undesirable effect on personnel and even properties are valued at millions of hard currencies is enormous. Experts from the electricity industry estimate that an average of 30-40% of all outages are connected to lightning-related events [9] [12]. This occurrence underlines a detailed study of the activity of lightning in power distribution networks. The lightning arrester is the most widely used system for the safety of the equipment in the substations and is linked between the line and the earth, i.e., parallel to the equipment to be protected [9].

An ideal lightning arrester should have the following characteristics;

1. No current should be drawn during normal operating conditions, i.e., and the sparks-over voltage must be above the usual or abnormal power frequency that may occur in the system.
2. To provide a conducting path to the field, any transient abnormal voltage above the breakdown value must cause it to break down as quickly as possible.
3. When the breakdown has occurred, resulting discharge current is carried out and the transient voltage falls below the breakdown value, the transient voltage through it exceeding the breakdown value.
4. Once the transient voltage has fallen below the breakdown value, the transient voltage increases.
5. The current of the power frequency following the breakdown must be interrupted.

There are many types of lightning arresters being used to protect the power grid. The lightning arrester options depend on the voltage and frequency, cost, weather condition, and reliability of the line.

The damage to the substation equipment caused by the moving wave as follows:

1. In the internal winding, the surge's high peak or crest voltage may cause flashover, thereby spoiling the winding insulation.
2. The steep wave-fronts of the surges may cause an external flashover between the terminals of the transformer.
3. The highest peak voltage of the surge may cause external flashover between the terminals of the electrical equipment, resulting in damage to the insulator.

Transmission lines are usually protected with overhead ground wires; this allows lightning strokes directed to the line to be immediately terminated down to the ground where the ground impedance is way much lower than the overhead lines as a protection system. transmission line surge arresters are often mounted on shielded lines where the resistance/impedance of the tower footing is higher and where it is not possible to have standard means of lower tower footing resistance. Such an installation phase is because there is a high possibility of insulation failure with a high footing resistance, thus following back flashovers. Furthermore, damaging the failure of shielding, which can contribute to insulation flashovers [43] [44] [46].

Incidents that are caused by lightning strokes on a transmission line plays a significant impact on the interruption of power supply. Transient and overvoltage experienced by the line due to the strokes can further cause damages to electrical and electronic equipment, leading to the breakdown of other critical equipment being fed by the line [44].

Entities have been experiencing such failure and failures due to lightning strokes, causing damages and equipment failure on their system. For instance, a case of a damaged lightning arrester was reported at the coast of the Sea of Japan (one of the entities owning a power system) lightning strokes with a huge amount of energy during winter seasons compared to one of the installed arresters were absorbed by it further causing damages on it. An investigation was held, and upon it, a conclusion was drawn to say failures of these arresters were due to lightning strikes which were said that they had a large amount of energy in winter, which is classified as winter lightning, taking note that not only arresters were damaged by this lightning and efficient countermeasure were damaged as well [46] [47].

Further observations from the investigations indicated that the liquid crystal camera that was used to conduct the investigation showed that when a strike occurred unto the structure and part of the lightning current flowed from the struck point through a service wire into the distribution line; which was concluded to be a lightning backflow current [27] [32].

The installation intervals of arresters play a significant role in protecting or damaging the distribution lines from lightning induced voltages. A shorter interval of a surge arrester installation was designed to protect the lightning-induced voltage distribution lines and arresters are not affected by it; it can also shield distribution lines from direct lightning strikes. [38] [41].

An arrester must endure the constant power-frequency voltage that it is meant to operate with. In the form of a current, it must discharge any transient energy from the device, thus preventing excessive voltage in the system. It must function in the same atmosphere as the equipment being secured. The capability of Temporary Overvoltage (TOV) shows the permissible overvoltage and length that an arrester can withstand without injury.

Many utilities use the monitoring of total leakage current of electricity (capacitive and resistive currents). To measure the leakage current of the surge arrester, the leakage current electricity sensors were used. However, as the total leakage current, which is merely capacitive, does not precisely mean the surge arrester's health, it is believed that this approach is not the foolproof method. Once the surge arrester has been blasted, there are problems even though the overall current leakage value was lower than the manufacturers' maximum.

The current in a lightning strike is likely to be in the 2-200kA range, so an efficient functional device is necessary to ensure asset security. The majority of structures use the BS6651 standard to report their design, testing, and maintenance works related to lightning protection. A "competent person" should conduct inspections to search for contractors with third-party accreditation of their ability to build and report on lightning protection systems as a good rule of thumb.

Significant parts of the lightning defense scheme likely are obscured or inaccessible after completion, it is crucial, and indeed appropriate, for the code to inspect every aspect of the lightning protection system during the construction phases of the installation. Any part of the device that will mask concealment upon completion must be given special attention. For aesthetic reasons, such elements can conceal, or the element would be required for the structure. Inspections should be carried out during the installation process, but also at regular intervals and upon completion.

2.12.1 Moisture leakage and contaminations

It can be challenging for certain arresters to distinguish whether weather moisture or partial discharge from the cavity, such as MOV type, is made up of block stack. Deciding whether moisture is the cause of failure becomes difficult as the arrester needs to be taken to the laboratory for proof indicating a gap for moisture ingress, showing signs of rusted metals that could only occur due to moisture [19] [27].

2.12.2 Excessive magnitude and duration of lightning surge

If the area is prone to lightning, there must be an assurance of a higher energy absorption to ensure that the arrester will not be damaged for the arrester to be installed.

Figure 2. 6: Lightning arrester: (a) burnt off and [29] (b) rusted [40]

2.14 Ways of protecting the surge arrester

Lightning arresters are an integral part of the insulation coordination design of the power system; hence are required to be reliable and available under the sTable condition and transient conditions. Furthermore, a power system with lightning arresters that have been in service for several years is still expected to have quality insulation to protect against any surges. For the arresters, an apparatus insulator's strength is coordinated with the arrester's protective level. The life span of lightning arresters is assessed by maintaining and ensuring it reliability in the field, by performing condition testing and maintain apparatus insulation throughout its service life [21] [25] [31].

The maximum stress that must be withstood by the equipment should also be below the basic insulation level given by the standard document of that particular arrester. Atmospheric conditions, environmental service equipment, and several other variables are considered when designing the thickness of the insulation. Coordination of insulation is the method of selecting the dielectric strength of the devices associated with the voltages that may occur on the system for which the system is intended, taking into account the service environment and the characteristics of the protective devices available. Methods to ensure proper protection for an arrester; such as tests at the laboratory to reveal the performance of the arrester, must be done, and also the protection of the arrester concerning switching surge stress is critically viewed before any installation takes place [32] [36].

To protect your arrester's condition, monitoring should be conducted for the resistive leakage current to determine if the insulation has been exposed to moisture ingress since the presence of high leakage current is a result of it. Conventionally this monitoring process was considered ineffective since high risks resulting from human error were detected when taking measures, errors and measurements misinterpretation were pointed, and this cost companies fortunes as some were replacing the arresters thinking that they are close to failure. The new method of conducting resistive leakage current uses an online monitoring system that is considered more accurate and cost-effective. The measurement result obtained for the leakage current test is directly proportional to the applied voltage and the surrounding temperature [50] [51].

The aging or degradation of an arrester can increase the resistive component of the leakage current. There are two groups of measuring procedures used on lightning arresters:

Online measurements –In a typical operation, the arrester is connected to the device and energized with the service voltage. For practical and safety reasons, the leakage current is usually measured on an arrester's earthed terminal ends. The arrester must be fitted with an insulated earth terminal to allow leakage current measurements that flow through the earth connection. The disadvantages of this measurement is that possibility of electrocution is high if employees are negligent or during human error. The advantages of this measurements are that safety precautions are implemented and are in place to protect employees.

Offline measurements - The arrester is removed and energized with a different source of voltage from the device. This type of measurement voltage sources that are AC/DC power systems can be used, and good accuracy can be attained by using them if adequate test voltage is available to be used [50] [51]. The advantage of this measurement is that it is safe and very result are mostly 98% accurate during testing.

CHAPTER THREE

ANALYSIS OF FIELD REPORT

3.1 Introduction

Research has been carried out worldwide for quite some time now, and several publications and national and international standards have evolved due to the increase in usage of lightning arresters in power substations [52]. This increase in demand is due to the adverse effects of voltage surge resulting from lightning strikes, switching, power follows current and fault induced on the various components used in power substation construct [53] [54]. A lightning strike is caused by lightning discharge when the associated current tries to find a path. In addition to this, lightning strikes on substations cause problems in electrical distribution networks; a strike alone on a conductor power line causes surge voltages with unsmooth voltage pulses at the strike point, propagated as traveling waves in either direction of the strike point. Also, surge voltages have high frequencies, meaning the current rise rate is more rapid than the average 50 Hz current [55] [56].

The significance of the rapid change of current is when it enters an inductance material in a transformer or reactor winding, the induced back electromotive force becomes so great that the insulation on the ends of the windings may fail. Transformer windings can be distorted due to the strong magnetic fields created by high voltage windings with high stresses accumulated between the adjacent turns and coil windings. Insulators can be damaged due to cracking, resulting in flashovers [57] [58]. An arrester aims to discharge surges of high voltage to the earth while protecting insulation and equipment, thereby interrupting current flows following a discharge.

In this study, an informal discussion has been carried out on lightning arresters. More than one substation field has been visited for information sourcing regarding lightning arrester usage, maintenance, testing procedures, and selection criteria. Captured in this work are research questions aimed at understanding the workings, challenges, principles used, and various field experiences.

Furthermore, this study aims to achieve the "best" design relative to a set of prioritized criteria or constraints. These include maximizing factors such as productivity, strength, reliability, longevity, efficiency, and utilization of lightning arresters, all of which are captured in the research questions.

This chapter is structured into three research questions; section one discusses the installation procedure of lightning arresters and types. Section two analyses the maintenance and testing criteria used on lightning arresters in substations, lastly section three gives an overview of the selection criteria used for lightning arrester systems.

3.2 Findings of research question one:

3.2.1 The objective of research question one

Research question one: What is the installation procedure used for lightning arresters, the type being installed, and benefits?

Research objective one: To establish the types and installation procedure of lightning arresters and their benefits regarding the protection of the substation system against surges.

3.2.2 Lightning arrester installation procedure, types and their benefits in substations

For installing a lightning arrester, the arrester must be installed as close as possible to the components requiring protection. This is to avoid compromising the working clearance distance for condition assessment, maintenance, and prioritizing a healthy and safe working environment. Additionally, the copper conductor's live part is connected to the lightning arrester while the neutral part is connected to the ground, which has an earthing mat or earth spikes less than or equal to the standard earth resistance used in South Africa. Structurally, the lightning arrester must be positioned perpendicular to the conductors' live phases. The arrester must also be installed on the incoming and outgoing phases of the transformer, circuit breakers and AC disconnects to avoid surges and faults damaging these components [59] [60].

Furthermore, to achieve a low resistance, the earth conductor length must be as short as possible, specifically, to a South African standard of less than one meter. Since low resistance is an essential requirement for earth conductors in the substation, copper material is preferably used in the design of conductors because of its high conductivity and low resistance property as the resistance of the conductor is directly proportional to the length of the conductor wire directly connected to the earth spikes or earth mat.

Moreover, the lightning arrester ratings must be taken into account. The lightning arrester ratings must be equal to or less than the basic insulation level of your equipment [61] [62]. For proper compliance with standards, there must be a specification on how the supplier should provide the arrester required, considering that equipment used in industries is guided by the public finance management act (PFMA).

Conventionally, porcelain housing types of lightning arresters were installed before being replaced by polymer housing types. The porcelain housing type of lightning arrester is well known for its high mechanical strength on the arrester and its infinite characteristic of showing no signs of aging when it comes in contact with moisture. Exposure to moisture has a long-term effect on this type of lightning arrester. In contrast, the polymer housing type of arrester is known for its good strength of adjusting itself on different environmental areas to reduce leakage current by enlarging the creepage distance, it repels water and is not prone to vandalism [63] [64] [65].

Additionally, environmental factors significantly impact lightning arrester performance and life span, especially for outdoor lightning arresters. Polymer types of arresters are mostly used in areas with high contamination, salt, or industries. A polymer rubber-metal oxide is usually recommended because it can be adjusted to accommodate these factors. They are designed in a disk shape and assembled into adjusTable stacks to give the desired creepage distance high enough to withstand high leakage current caused by salt particles, which causes flashover. The lightning arrester protects the substation's expensive components against voltage surges, which is beneficial to many utilities as they do not have to purchase or rebuild the substation due to explosion [66] [67].

3.3 Findings of research question two:

The objective for research question two was to obtain and understand how maintenance is carried out on the field's lightning arresters. This research has also been conducted to gain substantial knowledge on the testing procedures carried out before lightning arrester failure.

3.3.1 The objective of the research question two

Research question two: What maintenance, testing procedures are carried out on lightning arresters, and how does humidity affect the life span of an arrester?

Research objective two: To determine maintenance and testing being done on lightning arresters installed in substations and study the effect of humidity on the aging or degradation process of lightning arresters.

3.3.2 Maintenance procedures and testing of lightning arresters

To conduct maintenance and testing on lightning arresters, companies in South Africa are guided by SANS standards and safety regulations. This guide is done to keep lightning arresters in good condition and know the status of an arrester before they begin to fail. An authorized person who is a qualified employee or contractor with proper safety training and calibrated testing equipment can conduct condition monitoring and maintenance tasks on the arrester inside the substation with the required license, in South Africa an A-brown license is used. A trainee can only be allowed to enter the substation premises only if accompanied by A brown license holder to perform these test and maintenance task as part of his/her training [68] [69].

At a six a month's interval, condition assessment by visual inspection must be conducted on lightning arresters, check for bolts in high voltage clamps, high resistance, and bolts in earth connection clamps, if they are tight or not. Other checks carried out include discontinuity from base to earth checks, check for cracks, rust on metal parts, contaminations on connections, burnt marks on the copper conductor, carbon black spots due to flashes, alignment, and the clearance between the arrester and the phases. Failure to carry out these checks may cause the arrester to experience poor electrical connection as maintenance can elongate an arrester's life span. Additionally, regular maintenance is done every month, while testing is done every two years or more. Testing is vital since it ensures maximum service life and reduces any sudden chances of failure that may arise if not properly maintained and tested at a specified frequency by the producer [70] [71].

While conducting maintenance, cleaning, and removing black carbon on the arrester using cleaning agents are explicitly designed for arresters to avoid any obstruction from dust, which can lead to conductivity or cracking, thereby having an effect harmful on the arrester insulation properties. Also, deviations obtained from condition assessment must be rectified during every maintenance conducted.

Furthermore, to track if maintenance has been carried out within the specified or required frequency as part of compliance and life span check stated by producers, records for condition assessment and maintenance must be well kept. These records provide clarity on the arrester's behavior and allow Engineers to address any deviations within the arrester's life span [72] [73] [74].

Testing lightning arrester performance is vital to detect its nearness to failure; this will enable users to remove and replace them before failing to serve its purpose of protecting the components inside the substations.

Some test conducted on lightning arresters are:

Leakage current test- New arresters have a low leakage current; this prevents damages to the insulation, thereby compromising its performance. On continual usage, the leakage current increases with time, and each arrester has a maximum magnitude that must not be exceeded; if this magnitude is exceeded, the arrester is likely to fail. Also, the total leakage current is a phasor sum of capacitive and resistive leakage current. The resistive leakage current is good indicator of the surge arrester condition. Considerable increase in the resistive leakage current may be caused due to moisture ingress or premature aging of the arrester. In addition, the resistive leakage current has accepTable limits. For a new LA, the value of resistive leakage current should be less than 30 µA representing a normal condition. For an in service LA, the value of the resistive leakage current of 150 µA is accepTable. If the value of resistive leakage current is between 150 to 350 µA. When values are above 350µA the LA should be replaced immediately [75] [76] [77].

Thermo Vision-Scanning -This test helps in identifying hot spots in defective equipments found in substation. The objective of this test is to identify abnormal heat build-up in electrical equipment that appear normal to the eye. If the lightning arrester is defective more current will pass through the arrester under normal operating condition. So, the temperature inside the arrester will increase and this temperature can be detected with the use of thermal; vision scanning. Also, if the LA displays a temperature difference of a few °C from the nearby the arrester, it is placed on a watch list and checked again after a few weeks. Now, if the temperature differences increases then the arrester is placed on an emergency watch list. However, this does not require shut down of the switch yard equipment, it can be used in condition monitoring and preventive maintenance [78] [79].

Insulation resistance test- This test checks and verifies if the magnitude of resistance is still within the range of its ratings and in a good working condition. It is done to verify the quality of insulation of the equipment under test. Performing tests at regular intervals can detect insulation failures before they occur and prevents electrical accident. This measurement is to be carried out on individual stacks and then on the complete stack. A test voltage of 5 kV is applied using the insulation resistance test kit for a duration of 1 minute and values of 1 Giga ohm are generally considered as good values. Keeping a stack of low insulation resistance value will stress the other stacks which will eventually lead to failure of the LA. So, such stacks should be immediately replaced [80] [81].

Bell test- This type of test checks for cracks on the arrester by tapping; it is usually conducted on porcelain housing type of arresters. The ringing sound from the test indicates that the arrester is in excellent working condition, while a faint sound indicates the presence of cracks and the arrester needs to be replaced [82] [83].

The above tests are conducted on the field while the arrester is still mounted on the structure. However, there is no specific test to determine if the arrester has failed, but the methods mentioned above can only be used to determine the near possibility of failure. If the arrester is about to fail, comparing the magnitude of results after the tests can be used to check the possibility of failure. For example, the possibility of failure of a new lightning arrester having a leakage current of 30 mA with a maximum leakage current of 150 mA can be detected if the leakage current values are close to or above its maximum leakage current rating. This can also affect the life span of an arrester, which is between 25-30 years [84] [85].

For this thesis, Surveys have been carried out in the field based on engineers' experience using and testing lightning arresters. The aim was to find out how long it takes for lightning arresters to fail when exposed to higher temperatures and humidity. In the survey conducted, it was stated that environmental factors such as temperature and humidity changes negatively affect the aging process of lightning arresters. The rate at which water finds its way into the lightning arrester housing increases with an increase in humidity at a given temperature. Also, at high humidity in cold regions, the rate of evaporation is very low. When this occurs, it becomes very difficult for water that finds its way into the lightning arrester housing to evaporate. So constant exposure of lightning arresters to accumulated water due to low evaporation rate resulting from high humidity can reduce the life span of lightning arresters.

However, all these maintenance and tests being conducted still does not insinuate that a lightning arrester will last its life span. Environmental factors have a significant impact on the arrester's life span, lightning being one factor. Some areas have a high lightning flash density, which may affect the arresters' life span; installed arresters in such areas experience more lightning strikes than an average area. In addition to this, air pollution from industries can reduce arrester's insulation properties by reducing its insulation capability. Also, a lightning arrester installed on the coast can affect an arrester's life span since the sea produces salt particles blown out by the wind, resulting in the arrester having rusts and cracks earlier than expected.

3.4 Findings of research question three:

The drive and purpose for research question three were to understand how companies select the type of lightning arrester they need to be installed on the field and the selection criteria being used.

3.4.1 The objective of the research question three

Research question three: What selection criteria are used to select lightning arresters suiTable for substation protection?

Research objective three: Discover the selection criteria used when selecting lightning arresters for protection against high voltages.

3.4.2 Selection procedure for lightning arresters

For selecting an arrester, the substation configuration must be known, configurations such as grounding configurations (grounded or not grounded), circuit configuration (wye/delta), and taking note of nominal ratings based on the system ground configurations. For an ungrounded system, a higher arrester rating should be selected.

Additionally, knowing the arrester's ratings and ratings of the component being protected is critical to provide assurance protection of insulated components inside the substation. Also, the ratings for residual voltage on the arrester must be lower than the ratings of the lightning impulse voltage of the components being protected. This ensures that any surges above the lightning impulse voltage ratings are avoided to prevent damage to components in the substation. These components are expensive and must be taken care of. Also, a lower rating provides the highest margin of protection for the equipment's insulation system, even though it will increase the chances of failure.

There is a recommended limit for the voltage that can be applied continually; this limit is known as maximum continuous operation voltage (MCOV). Arrester ratings must be selected such that MCOV ratings are less than or equal to the maximum continuous voltages experienced by the arrester. Additionally, temporary overvoltage of the system must also be lower than the ratings of the arrester. Also, the basic insulation level (BIL) must be able to protect insulation against overvoltage. In summary, selecting an arrester that will discharge at a lower voltage level of required impulse voltage to cause a breakdown, the industry standards define the insulation and impulse level ratings

.

Most utilities on their traction substations use the stationary class type of arresters because of their high energy handling capability as they have their transformers rated above *20 mVA.* This type of arrester is expensive, and so as the components that need protection. The stationary type usually has its housing in a polymer insulation type; an example of this is the Metal Oxide (MO) arresters [86].

The MO arresters have a non-linear resistance meaning that under normal conditions, they behave like an insulator presenting high resistance as its component characteristics. When transient voltages are induced, it behaves like a conductor as the resistances reduce low enough to conduct any surges down to the ground. The line to ground voltage is also applied continuously between the line and ground terminals of the arrester. Hence lightning arrester carries minimal leakage current that can be withstood continuously [87] [88].

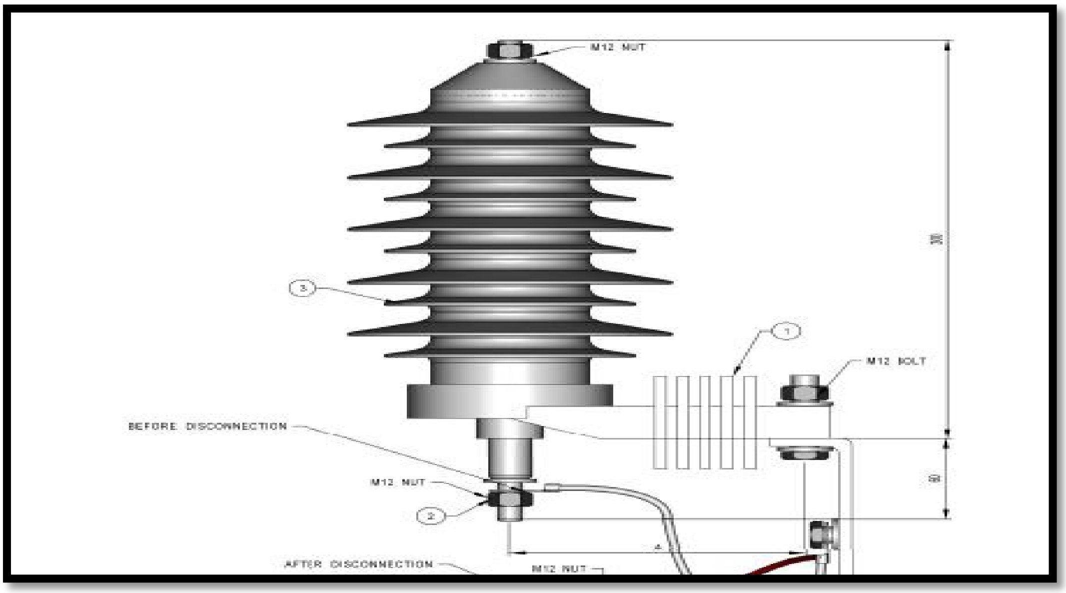

Figure 3. 1: Metal Oxide arrester type [86]

There are quite some factors that determine how many lightning arresters must be installed in a substation. One such factor is the number of phase wires present in the substation's incomer, which is known as the primary high voltage side. A 3 kV DC substation - a single unit – has seven lightning arresters and a double unit has 14 lightning arresters. While an AC substation has three lightning arresters for a single unit and six lightning arresters for a double unit. Additionally, AC substations have only two phases: incomers to the transformer and one from the secondary side to the line. While on the DC substation, three lightning arresters are connected on the primary side for protection of AC disconnects, primary circuit breakers, voltage, and current transformers, etc. Followed by another three lightning arresters to the transformer and one on the secondary side to the line [89] [90].

When an arrester fails, it is not advisable to repair it because the purchase and replacement of a failed one are more reliable and safer than using a repaired one. Also, the cost of repairing may be equal to or over purchasing a new one. When it has failed, transformers and any insulated equipment are likely to fail due to a lack of protection during transient overvoltage.

Conclusion

To maximize factors like increased life span, efficiency, and reliability, the type, selection criteria, maintenance, test, and installation procedure for lightning arresters used for protection against overvoltage in substations have been analyzed to guide users of lightning arresters. From the information gathered from the Survey, it has been stated conclusively that humidity as an environmental factor has been stated to affect the aging process of lightning arresters negatively.

CHAPTER FOUR

EFFECT OF TEMPERATURE ON THE FAILURE RATE OF LIGHTNING ARRESTERS USING WEIBULL PARAMETER ANALYSIS

4.1 Introduction

Humidity reflects a proportion of the air's water vapor that varies as the air temperature changes. In the presence of high humidity and fog conditions, the leakage current increases therefore causing harm to the arresters of the wave. Humidity area can easily result to the arrester's polymer surface to degrade earlier than expected. It feels oppressive outdoors when the humidity is high because water does not evaporate quickly. Water dries quicker when the humidity is inadequate because it is easier to evaporate more moisture [91] [92]. The aging of lightning arresters accelerates when lightning arresters are exposed to field conditions, including UV, temperature, humidity, voltage, salt fog, and rain.

Furthermore, moisture resulting from high humidity and internal partial discharges has a negative effect on the degradation of surge arresters for high voltage surges of metal oxide arresters. Partial discharge causes the arrester current to increase under the operating voltage. This phenomenon is hazardous and can cause the metal oxide arrester to have a complete outage. The intrusion of moisture will lead to internal discharges in the field. Adjustments in varistor voltage-current characteristics caused by moisture or partial discharges decrease free conditions of dry and partial discharge, such as less humid areas. [93] [94].

In addition to this, leaks at the end caps may allow water to enter the inner region due to improper sealing from insufficient compression of the gasket. Although the rate of moisture ingression is prolonged, it is observed that after years of field operation, the level of internal moisture rises to a sufficient level to have some effect on its operating characteristics. As the moisture content increases, the leakage current increases on the inner surface leading to partial discharges which can electrically affect the activity of the arrester [95] [96] [97]. Also, when moisture comes into an arrester, a degradation and failure of the voltage source are often found to be the fault mechanism. In severe cases, reducing dielectric strength can lead to a spontaneous system voltage failure or can fail to reseal after a lightning surge is discharged [98].

The rate at which these lightning arresters fail varies due to the influence of humidity on the rate at which the water contents that find their way into the lightning arrester evaporate. In an enclosed environment like the laboratory, the humidity is lower in an open space or field's humidity, resulting in a more increased evaporation rate and a more relaxed environment, which increases the lightning arrester service life [99] [101] [102]. Since highly reliable power systems usually require very high reliability over long periods of time of each system component used for its construction, components require test of reliability.

Accelerated ageing test is a test carried out on arresters it determines. It the reliability of the arrester under exposure to moisture resulting from the humidity of the environment where the arrester is installed. Also, degradation tests are commonly used to obtain reliability-test information more quickly which allows for modelling of failure causing mechanisms. Though degradation models can be used to predict or make inferences as regards the time of failure with the use of component failures and amount of degradation, but most models may be reliable because conditions of operation are not always the same. Furthermore, a testing facility could also be used to predict the time of failure of lightning arresters under operating conditions, one of such testing facility was developed by two decades back [63] [64].

Field conditions including UV, temperature, humidity, voltage, salt fog, and rain were simulated by the established multi-stress accelerated aging test facility. To determine the accelerated aging test's accelerating factor, a field exposure test at the outdoor test yard and characteristic study of field-operated specimens were used in this model. The result from the developed test facility showed quite a high deterioration soon after the ageing of the arrester accelerated. From the results of the developed test facility, degradations were found on the surfaces and in the interfaces of arresters. However, the developed test facility could not decide yet the accelerating factor of aging cycle. Conclusively, both developed models and test facility are however not a reliable method for determining the aging of lightning arresters [65] [66].

4.2 Cases of accelerating aging test

Two cases of acceleration aging test have been examined and are being presented to verify the consistency of results obtained from field survey as captured in chapter 3.

Case 1

The research aimed to study the behavior of lightning arresters when exposed to room temperature in an environment enclosed with the limited effect of humidity. A laboratory is a confined space, and it is critical to ensure that temperature and humidity are maintained to avoid any foreign objects such as dust, humidity and ultraviolet lights that can affect the outcome of the results. During the laboratory test, each lightning arrester was subjected to the testing temperature, and time was set to be 72 hours' maximum, and it was expected that the outcome results displayed true reflection of temperature could temper with arrester insulation.

Table 4. 1: Laboratory test results for failed and survived samples

Test outcome	**Laboratory temperature**
Failed	7
Survived	11

Case 2

Also, a similar test has been carried out on the lightning arrester in an open space or environment where temperature and humidity are variable and cannot be controlled or limited. For the field test, this took place on one of the six out nine substations, which are approximately 30 km apart, taking note that the area where this station falls under is Mpumalanga Province, which is known for its hot and humid weather condition. During the testing, various factors may have added impacted the results, such change in temperature; for instance, continuous exposure of heat on an arrester can results to an increase in internal pressure that may cause leakage current. The occurrence of leakage current for a repetitive number of times can result in moisture building up inside, which can further result in dielectric integrity reduction worst-case scenario being the failure of lightning arrester [5] [6] [7].

Table 4. 2: Field test results for failed and survived samples

Samples for field tests	110º C field temperature
Failed	10
Survived	8

4.3 Analysis of results for examined cases

Considering Table 4.1 and Table 4.2 for a laboratory test and the field test, respectively, the failure rate of lightning arresters tested in the field at 110 C is higher than in the laboratory. The outcome received from both tests results have been used to plot a Weibull cumulative distribution function graph. Parameters such as percentage cumulative failure probability have been calculated. The percentage cumulative failure probability "$F(i,n)$" is determined by counting the number of failed or degraded lightning arresters represented as "i" over a given period taking into accounts the total number of samples tested denoted with symbol "n." These arresters were subjected over 72 hours, an equivalent of three days. Also, the failure time t_i of each lightning arrester and the number of failed lightning arresters i during the degradation test were observed and recorded in Table 4.3 and Table 4.4.

Table 4. 3: Laboratory test result indicating the time of failure

t_i (time to failure) [Hrs]	(Failed arrester)
15	2
22	3
28	4
35	6
40	7
44	8
49	9

Table 4. 4: Field test results indicating the time of failure

t_i **(time To failure) [Hrs]**	**(Failed arresters)**
12	3
16	4
20	5
25	6
30	8
34	9
38	9
42	10
46	11
50	12

The number of tested samples n was the same for both cases and assigned a value of 18 representing the number of lightning arresters that were tested. The Time Equivalent of the Ageing (TEAP) $[t(eq. 40°C)]_i$ and the percentage Cumulative Failure Probability (CFP) $F(i, n)$ were calculated using Equation- (4.1) and Equation- (4.2) shown below, and the results were recorded in Table 4.5 and Table 4.6 to a test temperature of 110° C.

Table 4. 5: Calculated laboratory results for TEAP and CFP

$[\boldsymbol{t(eq.40°C)}]_i$	$\boldsymbol{F(i,n)}$
127.16	8.55
186.5	14.03
237.36	19.51
296.7	30.47
339.08	36
373	41.42
415.38	47

Table 4. 6: Calculated field results for TEAP and CFP

$[t(eq.40°C)]_i$	$F(i,n)$
101.73	14.03
135.63	19.51
169.54	25
211.93	30.47
254.31	41.42
288.22	47
322.13	47
356.04	52.38
389.95	57.86
423.86	63.34

For arresters testing, when the Weibull plot always has the cumulative failure probability on the vertical axis while the time taken for arrester to fail is on the horizontal axis, a negative slope shows reliability improvement. A positive slope shows reliability deterioration. No slope (a horizontal line) shows a table system [8] [9].

The Weibull plot for both test conditions generated and captured in figure 4.1 and figure 4.2.

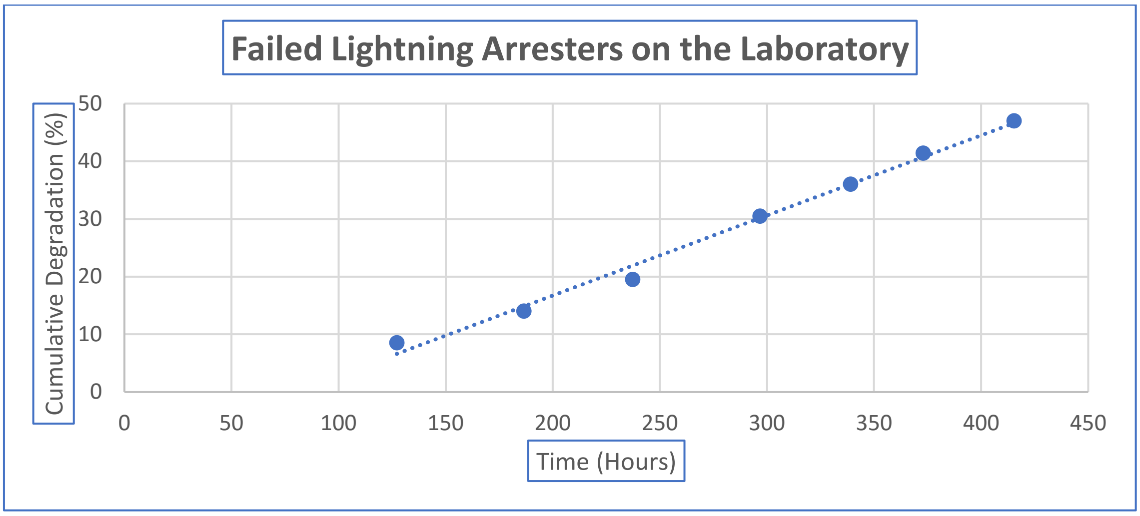

Figure 4. 1: Laboratory test result

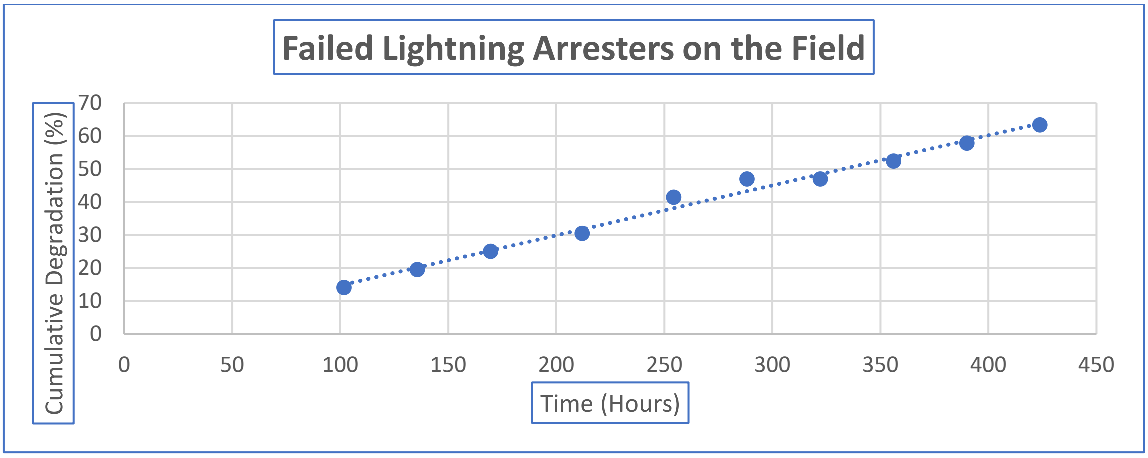

Figure 4. 2: Field test results

Since the values of calculating percentage cumulative failure $F(i,n)$ time equivalent to arrester operation at a service condition probability $[t(eq.40°C)]_i$ I am using Equation-(4.1) and Equation- (4.2) which are shown below, assume n is 18; t_i is 12, i is three and $T_{est\ temp}$ is 110° C.

Substitute these values into Equation- (41) and Equation- (2):

Recall Equation-(1)

$$F(i,n) \approx \left(\frac{i-0.44}{n+0.25}\right) \times 100 \qquad (1)$$

$F(i, n) \approx 14.03$

Recall Equation- (2)

$$[t(eq.40°C)]_i[hours] = t_i \times 2.5^{\frac{T_{test\ temp}-40}{10}} \quad (2)$$

$[t(eq.40°C)]_i = 101{,}73$

Now, $F(i, n)$ and $[t(eq.40°C)]_i$ are 14,03 and 101,73 as shown in Table 4. A similar calculation was carried out for the two test conditions using different t_i and i and the results were used to populate Table 4.5 and Table 4.6.

To verify the adequacy or the goodness of fit of the distributions obtained, for both the $F(i, n)$ and [teq:40 ºC] presented in figure 1, and figure 2, the logarithmic expression of percentage cumulative failure probability and service condition probability are represented as x_i and $y_i$respectively for both field and laboratory test.

To calculate the logarithmic value of the percentage cumulative failure probability and logarithmic of service condition probability, use Equation- (4.3) and Equation- (4.4) shown below respectively

$$x_i = ln\left[-ln\left(1 - \frac{F(i,n)}{100}\right)\right] \quad (3)$$

$$y_i = ln(teq.40°C)_i \quad (4)$$

Substituting $F(i, n) = 14.03$ and $[t(eq.40°C)]_i = 101{,}73$ results of Equation- (3.1) and Equation- (4.2) into Equation- (4.3) and Equation- (4.4) below, x_i and y_i becomes -2.41 and 4.85.

Similar calculations have been carried out using values of $F(i, n)$ and$[t(eq.40°C)]_i$ in Tables 5 and 6, for different test condition cases and the results captured in Tables 4.7 and 3.8.

Table 4. 7: logarithmic value for laboratory test

x_i	y_i
-2,41	4,85
-1,89	5,23
-1,53	5,47
-1,01	5,69
-0,81	5,83
-0,63	5,92
-0,45	6,03

Table 4. 8: Logarithmic value for field test

x_i	y_i
-1,89	4,62
-1,53	4,91
-1,25	5,13
-1,01	5,36
-0,63	5,54
-0,45	5,66
-0,45	5,77
-0,30	5,88
-0,15	5,97
-0,0035	6,05

4.2 Parameter analysis for the chosen test cases

The correlation function (γ) as a parameter needed to carry out a proper analysis of lightning will produce a constant failure rate when equal to 1 ($\gamma = 1$), which indicate a useful life span. If the parameter is less than 1 ($\gamma < 1$), the failure rate increases with time, resulting in infantile or early life failures. If ($\gamma > 1$), the failure rates increase with time meaning failures happen after a time has passed. [10] [11] [12]

The correlation function can be calculated as:

$$\gamma(x_i, y_i) = \frac{\sum(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \cdot \sum(y_i - \bar{y})^2}} \qquad (5)$$

where $\bar{x} = \frac{\sum x_i}{r}$ and $\bar{y} = \frac{\sum y_i}{r}$

Values of x_i and y_i in Table 4.7 and Table 4.8 for the test cases have been substituted into $\bar{x}$ and $\bar{y}$, and the result is presented in Table 4.9 and Table 4.10.

Since *r* is *10*, Now for the chosen instance, $\bar{x}$ and $\bar{y} =$ becomes *0.77* and *5.49*, respectively

Substitute $\bar{x}$ and $\bar{y}$ into Equation- (4.5):

$$\gamma(x_i, y_i) = \frac{\sum(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \cdot \sum(y_i - \bar{y})^2}} \qquad (5)$$

$$\gamma(x_i, y_i) = 3.83$$

This Parameter gives a statistical correlation between random variables, component based on the spatial or temporal distance between the variables used for the Weibull plots. Mathematically, correlation is an operation similar to a convolution function. It involves sliding the function over the other and finding the area under the overlapping regions [11] [13].

To calculate the slope function of the Weibull distribution (m), use:

$$m(x_i, y_i) = \frac{\sum(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sum(x_i - \bar{x})^2} \qquad (6)$$

Substitute $\bar{x}$ and $\bar{y}$ into Equation- (6) *m* becomes *3.22*. as captured in Table 9

Table.4.9 Laboratory test parameter

$\bar{x}$	$\bar{y}$	$\gamma(x_i, y_i)$	$m(x_i, y_i)$
-1.25	5,57	3.30	3.30

Similar calculations have been carried out for laboratory test and the result is presented in Table 4.10

Table 4. 9: Field test parameters Parameter 1

$\bar{x}$	$\bar{y}$	$\gamma(x_i, y_i)$	$m(x_i, y_i)$
-0,77	5,49	3,83	3,22

Other parameters calculated for proper failure analysis include the shape parameter(β), the intercept function (c), and the scale parameter α. The parameter for the Weibull form, β, is also known as the Weibull slope. This is because, in a probability map, the value of β equals the slope of the axis. Weibull distributions with β < 1 have a failure rate, known as infantile or early-life failures, that decreases with time. There is a relatively constant failure rate for Weibull distributions of β similar to or equal to 1, suggesting useful life or random failure. Weibull distributions of β 1 have a rate of failure that increases over time, referred to as wear-out failures. The scale parameter α has an opposite effect than the shape parameter(β) [10] [13]. The implication of this is that, as the shape parameter increases the scale parameter, the scale parameter reduces. However, the intercept function (c) drops. These three parameters can be calculated using Equation- (4.7), Equation- (4.8), Equation- (4.9) shown below, respectively [67] [68].

$$\beta = \frac{1}{m(x_i, y_i)} \tag{3.7}$$

$$c = \bar{y} - m(x_i, y_i) \cdot \bar{x} \tag{3.8}$$

$$\alpha = exp[\bar{y} - m(x_i, y_i) \cdot \bar{x}] \tag{3.9}$$

Substituting values of m, x_i, y_i, $\bar{x}$, and $\bar{y}$ into Equation- (4.7), Equation- (4.8), Equation- (4.9), the shape parameter(β), the intercept function (c), and the scale parameter α have been calculated as *0.31, 7.96* and *2864.07* respectively.

These parameters have been calculated for the chosen cases, and the result is presented in Table 4.11 and Table 4.12.

Table 4. 10: Laboratory test parameter 2

β	c	α
0,30	9,70	16317.61

Table 4. 11: Field test parameters 2

β	c	α
0,31	7,96	2864.07

Conclusively, the shape parameter (β) and scale parameter (α**)** have to be used to determine the failure rates for both test conditions captured in this chapter. Considering Table 4.9 and Table 4.10, the value of β for field and laboratory test conditions have been observed as *0.31* and *0.30,* respectively. It has been stated in section 4.3 that whenever a shape parameter (β) < 1, the failure rate decreases with time, leading to early life failures. From test results and calculation, the values for scaling Parameter for both test cases have been observed to be less than 1, so both test condition cases will provide an early life failure as a time of exposure increases [69] [70].

However, comparing the shape parameter for field and laboratory test results, it has been observed that the shape parameter for the field test result is greater than the shape parameter for the laboratory test results. The implication of this is that the lightning arresters tested on the field will fail earlier than those tested in the laboratory because as the shape parameter approaches 1, the failure rate increases. Since *0.31* is more significant than 0.30, we can conclude that the field samples have a higher failure rate than the laboratory samples.

Furthermore, as the scale parameter (α**)** increases, the failure rate increases with time. Considering the scale parameter for both chosen test cases recorded in Table 4.11 and Table 4.12, the field test result's scale parameter has been observed to be less than the laboratory.

Owing to this, we can conclude that arresters tested on the field fail earlier than those tested in the laboratory.

4.4 Conclusion

From the experiment carried out to determine the effect of temperature on the lightning arrester's aging process, it has been observed that environmental factors Influence temperature, which results in a change in humidity condition. Using the two Parameter (β) and (α), the Two case test shows that the tested lightning arresters' failure rate on the field is higher than the tested lightning arresters failure rates in the laboratory

CHAPTER FIVE

DISCUSSION OF RESULTS

5.1 Introduction

In order to ensure a high availability of the system, current system operators inside the substation must be routinely inspected and their electrical system properly maintained. [98] [99]. Hence regular testing maintenance and inspection on lightning arrester is crucial for surge protection and is also a requirement from the standard IEC 62305-3 to protect the system against lightning. The frequency of maintenance work depends on the factors listed below:

1. Loss of quality related to the weather and ambient condition.
2. Effect of direct lightning strikes and resulting in possible damage
3. The type of lightning arrester needed for the structure in consideration.

A maintenance routine is prepared, and a record should be kept for every work conducted to allow comparison between the latest results and those from current maintenance [100] [101] [102]. Following measures form part of the maintenance routine.

1. Cleaning the outside of the arrester housing helps minimize contaminations that can cause an arrester to conduct.
2. Before handling the arrester, the line must firstly be de-energized.
3. The ground relation should be tested regularly and measured.
4. To record measurements for the surge counter.
5. Directly connected to the arrester and line conductor is the line lead.
6. The ground lead is firmly clamped to the terminals of the arrester and the ground value.

4.3 How to conduct lightning arrester testing

Testing is conducted to ensure the integrity of lightning arrester as protection equipment onto the substation components before it tends to fail [6][7]. There are various types of testing conducted to ensure reliable protection of an arrester, and there are:

Visual inspection – This inspection is conducted at fixed intervals of no greater than 12 months depending on the make or type of an arrester being installed. Inspect mechanical condition of all conductors if there not cut or damaged, check if an arrester is still within the required clearance, bonds if there still in place and not damaged, joints and earth electrodes bolts should be inspected and checked if there are appropriately tightened not loose [60] [61].

Thermal image monitoring (infrared testing)-the reason why thermal imaging can determine surge arrester health is that during steady-state activity, these components dissipate very little energy and seldom exhibit a temperature far higher than ambient. Thermal imaging and 3rd harmonic leakage current monitoring are the two best methods for determining the condition of arresters. Measuring the 3rd harmonic leakage current flowing under normal circumstances through the ZnO arrester provides details about the actual operating state of the arrester. Some methods have been developed in the last five years to determine the condition of surge arresters. Many researchers have established the surge arrester condition based on the third harmonic leakage current. There is still a lack of practical thermal imaging guidance for surge protection control, although much has been done with surge monitoring. [63] [64].

The advantage of thermal imaging is the speed of data collection, even if there is no quicker way to show whether an arrester is near the end of life than a temperature scan. Also, it does an excellent job from a distance, particularly when using a long-range camera lens. One downside is that no thermal imaging systems on the market are capable of remotely transmitting data. As such, it takes a person to physically go to the site and gather data to obtain a thermal profile for the arrester [8] [9] [10].

Usually, it will emit heat when an arrester is in the process of failing. At the same time, a lightning strike or switch surge can damage an arrester just days after its last thermal scan, possibly the only negative point regarding thermal imaging seems to be the potential for failure between successive scans.

<u>Power factor testing</u> – this type of testing is susceptible to weather conductions. This type of test is done wherever possible in favorable circumstances. Measurements on an arrester are often carried out at the same or prescribed test voltage, as it is possible to integrate nonlinear elements into an arrester. In order to calculate the integrity of an arrester and isolate potential failure hazards, power loss calculation is also an effective tool. This type of test demonstrates conditions that could affect an arrester's protective role, such as the presence of moisture, salt deposits, corrosion, broken porcelain, open shunt resistance, faulty pre-ionizing parts, and defective gaps. This type of test should not be performed on a complete multi-unit arrester stack, but on an individual arrester unit. A single arrester unit will measure the standard unground specimen test (UST) in the laboratory. However, when placed on a support system in the field, it can only be tested by grounded specimen test (GST) [67] [68] [69].

<u>Dead earth testing method</u> – Any low-resistance earth not directly or unexpectedly linked to the earth under test may be this method.

A connection made from the appropriate earth to the test meter, which is attached to the electrode under examination, will display a lightning protection system operating known as the dead earth. A reading is taken, and the obtained ohmic value is the resistance of the electrode sequence under test and the resistance of the dead earth constructively.

Benefits of lightning arrester testing

It ensures that all vital electrical and electronic installations are protected from the effect of a lightning strike when safety testing against lightning is carried out. The economic benefits are measured as follows: how does the average annual cost of a lightning system relate to the cost of a lightning system? [11] [12].

4.4 Installation

An arrester must be mounted in the pothead yard at the OHL entrance to the substation to protect against lightning in a high voltage substation. This helps to reduce the lightning overvoltage amplitude that reaches the substation and to secure equipment in the pothead yard (instrument transformers). To secure its insulation, the second set of arresters must be located as near as possible to the power transformer [13] [14].

The installation of a lightning arrester can also minimize the circuit breaker's operation with any possible system outage resulting from a back flashover. A short circuit needs to be avoided on a power system to ensure continuous electricity supply for consumers and prevent stresses and damages that may result in the power system. One factor that can prove a short circuit in the system is insulation faults on a transmission line in front of a substation. Insulation flashover can result in the formation of surges with a very steep front that enters the substation and causes insulation stresses, especially on transformer windings.

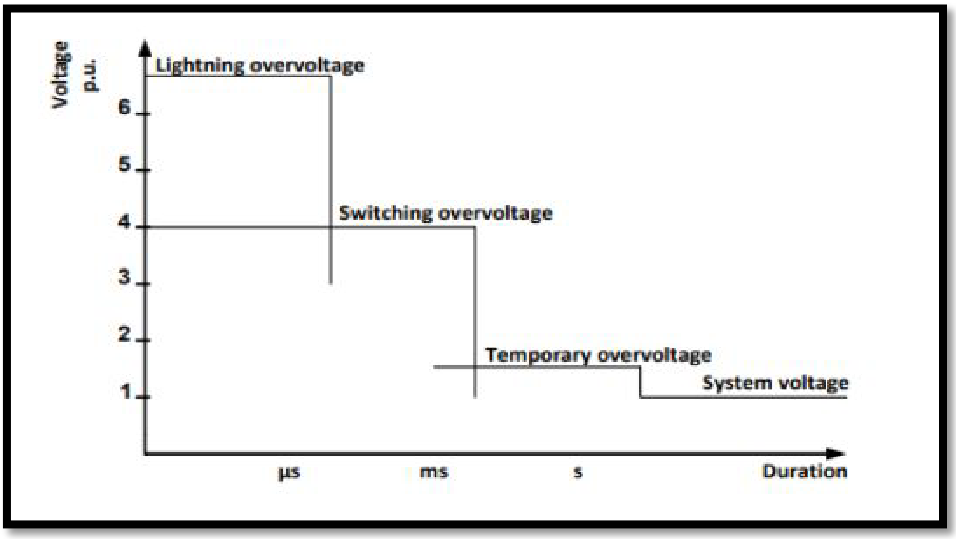

Figure 5. 1: Types of surges experienced by a substation

5.3.1 Lightning overvoltage and switching

Lightning overvoltage is caused by external events. Such events may result from lightning flash terminating on the phase conductor of the transmission line is more likely to happen in an unshielded line [15] [16]. The phenomenon of lightning hits on the conductor of a shielded line is usually denoted as shielding failure. Back flashover is the result of a direct lightning strike to the tower structure and shielded wires. Lightning surges move to the ground in both directions and down the tower, generating a cross-arm voltage and stressing the insulation. Flashover occurs when the voltage exceeds the threshold of the insulator string. The flashover of the insulator then causes a line to ground fault and will be interrupted by the breakers. The back flash usually occurs during lightning striking the overhead shield wire where the ground impedance is high. Switching overvoltage usually results from the breaker operation, including fault occurrence, line energization, reclosing, capacitor switching [17] [18].

5.2.2 Temporary overvoltage

Temporary overvoltage generally lasts for hundreds of milliseconds or longer, although hundreds of microseconds normally last for the switching overvoltage. This then makes a major difference between the overvoltage of the switch and the temporary overvoltage. The temporary overvoltage has a frequency that is close to the standard power frequency. The leading causes of the temporary overvoltage include single line-to-ground faults, Ferro resonance, load rejection, loss of ground, coupled-line resonance, and transformer-line inrush. This type of over-voltage is crucial when determining an arrester selection and installation [19] [20].

5.4 Selection parameters for lightning arresters used in substation equipment protection

In principle, the main aim in choosing the arrester is to select the least graded lightning arrester that provides sufficient protection for the equipment's insulation and that it should be rated so that when connected to the power grid, it will have an adequate service life. Also a highly rated surge arrester should not be used because it increases the capacity of the arrester to work in the power system but reduces the protective margin for a specific degree of insulation.

Furthermore, to ensure that an arrester performs the desired system protection function without causing any problem in the system, an arrester parameter must be appropriately selected. Therefore, application technicians, engineers, and users must be aware of the essential parameters to consider when choosing arrester types for substation safety. Some of these parameters are:

- ➢ Continuous operating voltage,
- ➢ Arrester rated voltage
- ➢ Nominal discharge current
- ➢ Thermal energy rating

5.4.1 Continuous operating voltage

The earthing of the transformer neutral and the system's failure conditions determine the continuous operating voltage U_C. This value is the maximum accepTable value of a sinusoidal power frequency between the system terminals. It is dependent on whether the arrester is connected between phase and earth, between the phases, or between neutral and earth. Since sudden voltage rise leads to damage of substation systems, the worst-case voltage increase depends on the system's neutral earthing configuration, which will directly affect the U_C selection. The value of U_C is selected with a special consideration using the highest actual system voltage U_S as a reference. If the actual system voltage value is not known, the highest voltage for the equipment should be taken as a reference. Typically, arresters are connected phase to the ground, so U_C should be equal or greater than one third the value of U_m [21] [22].

Additionally, when determining the value of U_C the Potential temporary U_{TOV} overvoltage must be considered by medium-voltage systems in substations. U_{TOV} occur during earth faults and is dependent on the transformers' star point treatment and system management. To calculate the potential temporary overvoltage, which is dependent on the continuous overvoltage and T, which is a function of TOV curves found in the manufacturer's data sheet use:

$$U_C \geq U_{TOV}/T \qquad 5.1$$

TOV is relatively long-term (i.e. seconds, even minutes), un moistened, or slightly damped power-frequency overvoltage. Usually, these over voltages are triggered by grounding faults, resonance conditions. TOVs can be described by their frequency of oscillation, being higher, equal or lower than the frequency of power. Load rejection, unloaded transformer energization, or a combination of these. TOVs are usually accompanied by a transient overvoltage resulting from a switching operation is often followed and triggered by minimal damping under operating conditions, a condition that can often be associated with light load or no load at all [22] [23] [24].

Fault to ground, load rejection, Ferro-resonance transformer energization, the combination of transient origin of overvoltage, and longitudinal overvoltage are the key causes of TOVs. The TOV level has become a defining criterion for selecting the rated arrester voltage and the permanent material overvoltage level. An exception, However, Resonant and Ferro-resonant overvoltage are an exception. They should not be used for arrester selection; instead, they should be limited by detuning the system from the resonant frequency, changing the system configuration, or by installing damping resistors [25] [26].

Furthermore, another parameter that could be used to determine the value of U_C is the fault factor K, which determines the value of temporary overvoltage on the system. When these values are presented in the manufacturer's datasheet, the value of parameter U_C can be calculated using the appropriate formula. Also, fault factor could reach higher values under certain circumstances as a result of resonant phenomena; in such cases, the U_C value should be increased accordingly [24].

Conclusively, for an arrester connected phase to earth, the value of U_C must be greater than U_S, but when the arrester is installed neutral to earth, the value of U_C must be greater than U_S divided by K, where K is 1.732 for an ineffectively earthed system [25].

5.4.2 Arrester rated voltage

This voltage is simply used as a benchmark for the functional features. It can be defined as the maximum permissible r.m.s. value of the power-frequency voltage between the terminals at which it is constructed to operate properly under the temporary overvoltage conditions as calculated in the high or long-term operating duty pulse tests. Though it is of no particular significance to engineer, it is used to define the arrester's operating characteristics when used as the reference parameter and represented as U_r.

It is important to note that Ur's value depends on the actual system voltage U_S for a solidly earthed neural system and isolated or resonant earthed neutral system.

For a solidly earthed neutral system U_r can be calculated as

$$U_r \geq 1.25 \times 1.05 \times \frac{U_S}{\sqrt{3}} \qquad 5.2$$

Where U_S is a function of U_C, which is represented as:

$$\frac{U_C\sqrt{3}}{1.05} \geq U_S \qquad 5.3$$

For an isolated or resonant earthed neutral system U_r can be calculated as:

$$U_r \geq 1.25 \times U_S \qquad 5.4$$

In this case U_S as a function of U_C is represented as:

$$U_C \geq U_S \qquad 5.5$$

However, the required rated voltage can also be calculated by examining the temporary overvoltage that may occur in the system. Using Eq (5.1), the value of U_C can be calculated by taking TOV's value from the manufacturer's datasheet. It should be noted that the TOV value on the datasheet should be greater than the TOV at the substation arrester location if not Ur and U_C are increased; in fact, the U_r, TOV, and U_C are all link parameters, and careful analysis should be carried out when selecting these parameters.

5.4.3 Nominal Discharge Current

Another critical parameter to consider in the selection of lightning arresters to be used in the substation is the nominal discharge current. For the description of an arrester in IEC standards 60099-4, 60099-6, and 60099-88, the peak value of the lightning current impulse is used. Technically, it is determined from the normal maximum amplitude of the lightning current that can be expected in the substation for which insulation coordination is carried out through the lightning safety level of the arrester [66] [67].

These values do not however, reveal anything explicitly about the operating characteristics of the arrester used to safeguard the substation. The actual purpose of knowing the nominal discharge current value is to identify various additional demands and test specifications, which depends on the class of arrester used in the substation equipment protection. The nominal discharge current can be used to calculate the lightning impulse protection level LIPL of lightning arrester. Having a sound knowledge of the LIPL allows for a complete evaluation of the lightning performance of transmission lines connected to substations [68] [69], it can be represented using I_n.

5.4.4 Thermal energy rating

The thermal energy rating is the energy that an arrester will dissolve without prompting any thermal runaway in a thermal recovery test. Thermal Rating as given by the manufacturer and tested using specific thermal recovery tests depending on the type of arrester intended for use in the substation, both station and distribution class arresters. For station class arresters applied to systems with Us 52≥kV and coulombs for distribution class arresters rated US 52≤kV, the thermal energy level will be expressed in joules. Station class arresters with U_S rated below *52kV* can be tested and rated in the same manner as ratings $U_S \geq 52kV$. This parameter is represented as W_{th}.

Having a sound knowledge of the above-measured parameters will allow for the right decision to be taken regarding the type of arrester to be used for the substation equipment protection at minimum cost and maximum efficiency, which is the primary goal of modern-day engineering system protection. However, the selection of these various voltages, current, and energy parameters needed for the selection of lightning arrester is mainly dependent on whether the system is grounded or not; if the system is grounded, it is also essential to know the type of grounding employed. [69] [70] [71].

5.4 Comparison of field test results with surveys results

The Surveys indicated that the test conducted on lightning arresters in a substation resulted in nine failures out of twenty-seven arresters, one per substation. Also, the records indicated that during the testing period, weather conditions ranged from *1 °C* to *10 °C* in winter, and this poor weather had a massive impact on the outcome of the results. An area from Mpumalanga is frigid during winter and extremely hot during summer; hence, it is highly humid.

The high humidity results in slow ionization of moisture on the internal part of an arrester, which affects an arrester's performance and ability to protect the system on a substation as moisture results in leakage current that causes premature failure to an arrester. Also, during frigid weather at high humidity, the rate of evaporation of water from the lightning arrester housing is slow, so when water is constantly contained in the lightning arrester, it reduces the arrester's life span. From the records, the captured information presented the below information:

Table 5. 1: logarithmic values from field Survey

t_i **(time to failure)**	**(Failed arresters)**
14	2
15	2
16	3
18	4
19	4
21	5
23	6
24	6
26	7

From the above results displayed during the Survey, which were captured on the logbook inside the substation, other calculations time equivalent for an arrester an arrester operation and the cumulative percentage failure to indicate how long it took for an arrester to fail.

Table 5. 2: Calculated Surveyed results

$[\boldsymbol{t}(\boldsymbol{eq.}\,\mathbf{40}°\boldsymbol{C})]_{\boldsymbol{i}}$	$\boldsymbol{F}(\boldsymbol{i},\boldsymbol{n})$
71,21	5,72
76,29	5,72
81,38	9,39
91,55	13,06
96,64	13,06
106,8	16,73
116,98	20,40
122,07	20,40
132,24	24,07

Using the results above, a graph was populated, it was obtained that the first lightning arrester failed at 71 hours while subjected at 100°C, which is lesser than the field test temperature 110°C; this implies that the cold weathers had an impact on the outcome of the results hence the time of failure was reduced from 101 to 71 hours.

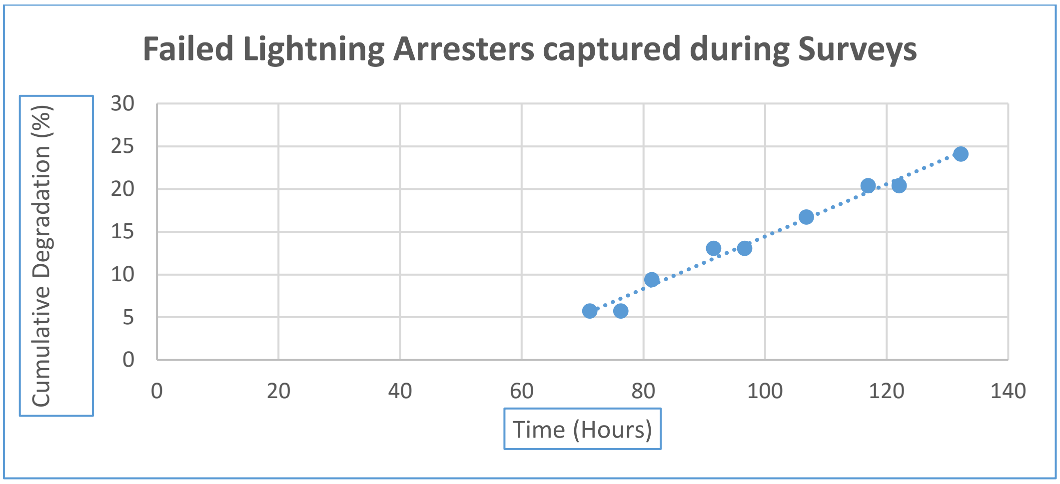

Figure 5. 2: Survey test results

From the values of $[t(eq.40°C)]_i$ and $F(i,n)$ were taken from logbook from field Survey, the values of x_i and y_i have been calculated and recorded in Table. 5.3. This calculation allows for proper analysis and comparison of results obtained from field Surveys and experimental analysis results as captured in chapter 3. During lightning arrester testing, the values of xi and yi are vital parameters to be considered when carrying out a degradation test on lightning arresters.

Table 5. 3: logarithmic value from Surveys

x_i	y_i
-2,83	4,27
-2,83	4,33
-2,32	4,40
-1,97	4,52
-1,97	4,57
-1,70	4,67
-1,48	4,76
-1,48	4,80
-1,29	4,88

The results above further calculations were carried out to get parameters for shape parameter(β), the intercept function (c), and the scale parameter α.

Table 5. 4 Calculated Survey: (a) for parameter 1 (b) for parameter 2

$\bar{x}$	$\bar{y}$	$\gamma(x_i, y_i)$	$m(x_i, y_i)$
0,12	-0,02	2,62	1,84

$\bar{x}$	$\bar{y}$	$\gamma(x_i, y_i)$	$m(x_i, y_i)$
-0,77	5,49	3,83	3,22

Table 5. 5: Field test: (a) for parameters 1 (b) for parameters 2

β	c	α
0,54	8,24	3789.54

β	c	α
0.31	7.96	2864.07

As stated in chapter 3, the value shape parameter β in the Weibull distributions is β < 1, the failure rate decreases with time, indicating an early-life failure. There is a relatively constant failure rate of Weibull distributions with β near to or equal to 1, suggesting useful life or random failures. Weibull distributions with β > 1 have a failure rate that increases with time resulting in wear-out failures. From Table5.5, the value of the shape parameter gotten from the Survey report is observed to be less than 1, indicating an early life failure, which is also the case of experimental field result as captured in chapter 3. This further verifies the statement that lightning arresters installed in highly humid areas age faster than those installed in less humid areas, as captured in chapter 3 [101] [102].

Now comparing the value of shape parameters for Survey report with experimental field result, it is observed that the value of shape parameter from field test result is less than the value calculated from Survey result as captured in Table 5.5 and Table 3.12. The reason for this difference in values is a result of the difference in the time of exposure of the arresters to the chosen test temperature.

Conclusion

To further verify the consistency of the results obtained from the field, the various maintenance and installation processes have been analyzed and discussed extensively. Conclusively, it has been observed that the rate at which lightning arresters degrades is mainly dependent on the humidity of the environment in which these arresters are installed. In highly humid areas, the rate of evaporation of water from the lightning arrester housing is slow, leading to water accumulating in the arrester housing for a more extended period. This accumulation causes the arrester to degrade. When the arrester is installed in less humid areas, the water that finds its way into the arrester housing evaporates quickly, thus providing an increased life span.

CHAPTER SIX

CONCLUSION

The lightning arrester as an equipment that function during high voltage lightning and pulses has been studied as a by passer of surge current on the field. When the travelling waves produced by lightning hit the windings of the transformer, it causes considerable damage. The inductance of the windings then opposes any sudden passage of electricity charge through it. Therefore, the electric charges “piles up” against the transformer in the substation. This induces such an excessive pressure between the windings that the insulation may breakdown, resulting in the production of arc. Also, the travelling waves produced by lightning surges can shatter insulators and wreck poles. Whenever lightning strikes at any point in the network, it propagates from that point of incidence to other parts of the network. The propagation is such that the voltage surge magnitude increases as the voltage level decreases. This implies that consumer loads located at the low voltage levels will experience the highest effect of any lightning strike. Since the reliability of service delivery is largely dependent on the performance of this protective equipment, it is important for a proper analysis to be carried out on the safe working condition of this equipment which have been captured in this thesis as a guide for users of lightning arresters.

From the experiment carried out to determine the effect of humidity on the ageing process of lightning arrester, it has been observed that environmental factor influences temperature which results in change in humidity condition. Humidity leads to moisture ingress resulting in the degradation of arresters installed in the substation. For the two cases of test condition captured in chapter three, a drop in temperature has been observed as a result of environmental factors. This affects the rate of evaporation of water that finds its way into the lightning arrester housing.

The first case of test condition captured in chapter three presented a laboratory test set up where there is little or no change in humidity as a resulting of environmental factor. The low humidity of the laboratory allowed for an increase in the rate of evaporation of water that finds its way into to the lightning arrester housing. If the rate of evaporation of water is slow, the time at which the unwanted water in the lightning arrester housing accumulate is increased. As the time of accumulation increase, the life span of the lightning arrester is reduced because of induced internal partial discharges in the lightning arrester.

Considering the field test experiment set up, environmental factors increases the humidity leading to a reduction in the rate of evaporation of water from the housing of the arrester. For the test carried out in the laboratory, it has been observed that in a total sample of 18 arresters, 7 arresters failed while 11 arresters survived. Comparing these values of failed and survived arresters, the field test set up produced a total of 10 failed samples and 8 survived samples. It is observed that the failure rate is higher in the field experiment compared to the laboratory experiment. From the Weibull plots failure rates for both cases have been predicted with the use of parameters such as shape parameter and scale parameter.

A condition of shape parameter less than 1 have been considered as an early life failure. Both test condition produced a shape parameter of less than 1, signifying early failure rate for both test cases. However, there is difference in the shape parameter for the two test condition. The shape Parameter for the field has been observed to be greater than the shape parameter of the laboratory test results. What this implies is that the lightning arresters tested in the field will fail earlier than those tested in the laboratory because as the shape parameter approaches 1 the failure rate increases. Since 0.31 is greater than 0.30 we can conclude that the field samples have a higher failure rate than the laboratory samples. Considering the scale parameters for the chosen cases the scale parameter for the field test have been observed to be less than that of the laboratory test condition, we can conclude that the arrester on field failed earlier than those tested in the laboratory even though both have early life failures. The number of failed and survived samples gotten from a survey of field visit has been compared with the experimental values of field and laboratory test values in chapter five and it is observed to be consistent with the experimental values captured in chapter three.

Conclusively, to maximize factors like increased life span, efficiency and reliability, the type, selection criteria, maintenance, test and installation procedure for lightning arresters used for protection against over voltages in substation have been analyzed to serve as a guide for users of lightning arresters.

Future work of research

With the introduction of internet of things IOT, there is a need for lightning arresters installed in substation for equipment protection against system over voltages to be smart enough to predict the moisture content in the arrester housing and send a signal to the substation control room via the internet so that the arrester will be replaced before it causes damage to the equipment it is protecting. Also, when an arrester is about to get to its useful life span, it is important that the time of failure should be known without visiting the site to check the arrester physically.

The future work of this research involves designing a programmable arrester that can predict the level of moisture ingress that can cause damage or reduce the life span of the arrester and send signal to the substation control room over a network without carrying out any physical test on the installed arrester.

REFERENCES

[1] R. Gore, H. Satheesh, M. Varier and S. Valsan, "Analysis of an IEC 61850 based Electric Substation Communication Architecture," *7th International Conference on Intelligent Systems, Modelling and Simulation*, Bangalore, India, 2016.

[2] M. Golshani, G. A. Taylor and I. Pisica, "Simulation of power system substation communications architecture based on IEC 61850 standard," *in Power Engineering Conference (UPEC)*, 49th international Universities , 2014.

[3] T. Yang, R. Zhao, W. Zhang and Q. Yang, "On the Modeling and Analysis of Communication Traffic in Intelligent Electric Power Substations," *IEEE Transactions on Power Delivery*, vol. VOL. 32, no. NO. 3, pp. 1329-1330, JUNE 2017.

[4] P. Pakonen, B. A. Siddiqui and P. Verho, "A Novel Concept of Secondary Substation Monitoring: Possibilities and Challenges," *in EEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, Melbourne, Australia, Nov 28 - Dec 1, 2016.

[5] J. M. Boggess, G. W. Becker and M. K. Mitchell, "Storm & Flood Hardening of Electrical Substations," IEEE, 2016.

[6] C. S. W. Q. Association, "Introduction to Hydromodification," Carlifornia, April 29, 2009.

[7] S. J. Almond, S. Baird, B. F. Flynn, D. J. Hawkins, and A. J. Mackrell, "Integrated Protection and Control Communications outwith the Substation," in Cyber Security Challenges, GE Energy, UK, 2007.

[8] J. Matt Cole, "Challenges of Implementing Substation Hardware Upgrades for NERC CIP Version 5 Compliance to Enhance Cybersecurity*," in IEEE, Chattanooga*, TN, USA, 2016.

[9] I. Rahmati and M. IFotuhi-Firuzabad, "Reliability evaluation of HV substations in the presence of Fault Current Limiter," *in IEEE Bucharest Power Tech Conference, Bucharest, Romania*, June 28th - July 2nd, 2009.

[10] P. Barkan,, "Reliability Implications in the Design of Fault Current Limiters," *IEEE Transactions on Power Apparatus and Systems*, Vols. Vol. PAS-99, no. No.5, Sept/Oct 1980.

[11] L. Ye, "Behavior Investigations of Superconducting Fault CurrentLimiters in Power Systems," *IEEE Transactions on Applied Superconductivity*, vol. Vol. 16, no. No. 2, June 2006.

[12] T. Bernstein, "Lightning and Power Surge Damage to Appliances," *IEEE Transactions on Industry Applications*, Vols. Vol. IA-20, no. NO. 6, pp. 1507-15010, November/December 1984.

[13] A. Piantini and J. M. Janiszewski, "Lightning-caused Transformer Failures in Distribution Systems," *in International Conference on Lightning Protection (ICLP)*, Shanghai, China, 2014.

[14] I. W. G. 3.4.11, "Application of Surge Protective Devices Subcommittee," *Transactions on Power Delivery*, vol. No. 7, no. No.1, pp. 302-309, January 1992.

[15] L. Montañés, M. García-Gracia, M. Sanz and M. A. García, "An Improvement for the Selection of Surge Arresters Based on the Evaluation of the Failure Probability," *IEEE Transactions on Power Delivery*, vol. No. 17, no. No. 1, pp. 123-127, January 2002.

[16] N. K. Htwe, "Analysis and Design Selection of Lightning Arrester for Distribution Substation," in World Academy of Science,, 2008.

[17] T. E. McDermott, T. A. Short and J. G. Anderson, "Lightning Protection Of Distribution Lines," *IEEE Transactions on Power Delivery,* vol. Vol. 9, no. No. 1, pp. 138-142, January 1994.

[18] R. E. Clayton, I. S. Grant, D. E. Hedman and D. D. Wilson, "Surge Arrester Protection and Very Fast Surges" *IEEE Transactions on Power Apparatus and Systems*, Vols. Vol. PAS-102, no. No. 8, p. 2407, August 1983.

[19] H. Linck, "Lightning Arrester Field Test Equipment and Results," *in AIEE CPS8-160*, October 1959.

[20] R. S. Pearson and H. O. Hartley, Biometrika Tables for Statisticians, vol. Vol. I, Cambridge, England: Cambridge University Press, 1959.

[21] D. G. Kasten, S. A. Sebo and J. L. Lauletta, High Voltage Diagnostic Measurements For Surge Arrester Condition Monitoring, Columbus, OH 43235, USA: The Ohio State University, Department of ECE.

[22] M. S. Ariffin, "Challenges in Developing Surge Arrester Failure Detection Methodologies in Tnb Distribution Network," *in 20th International Conference on Electricity Distribution*, Prague, 8-11 June 2009.

[23] J. L. Puri, N. C. Abi-Samra, T. J. Dionise and D. R. Smith, "Lightning induced failures in distribution transformers," *IEEE Trans. Power Delivery*, vol. Vol. 3, no. No. 4, pp. 1784-1801, October 1998.

[24] P. O. Oluseyi, T. O. Akinbulire and O. Amahian, "Investigation of The Lightning Arrester Operation in Electric Power Distribution Network," *Nigerian Journal of Technology (NIJOTECH)*, vol. Vol. 37, no. No. 2, pp. 490-497, April 2018.

[25] R. W. Flugum, "Operation of Lightning Arresters on Abnormal Power Frequency Voltages*," IEEE Transactions On Power Apparatus And Systems*, Vols. Vol. Pas-89, No. No. 7, Pp. 1444-1454, September/October 1970.

[26] K. Nakada, T. Wakai, H. Taniguchi and T. Kawabata, "Distribution Arrester Failures Caused by Lightning Current Flowing from Customer's Structure into Distribution Lines," *IEEE Transactions on Power Delivery*, Vol. 14, no. No. 4, pp. 1527-1532, October 1999.

[27] Krystian Leonard Chrzan, "Influence of moisture and partial discharges on the degradation of high-voltage surge arresters"*European Transactions on Electrical Power,* 19 May 2004, pp. 175-184.

[28] K. Mokhtari, M. Mirzaie and M. Shahabi, "Leakage Current Analysis of Polymer and Porcelain Housed Metal Oxide Surge Arresters in Humid Ambient Conditions*", Iranian Journal of Electrical and Electronic Engineering,* vol. 11, no. 1 pp 79-86, March 2015.

[29] M. K. Zadeh, H. Abniki and A. A. Shayegani Akmal, "The Modeling of Metal-Oxide Surge Arrester Applied to Improve Surge Protection," *in 2nd International Conference on Power Electronics and Intelligent Transportation System,* Tehran, Iran, 2009.

[30] D. Meixin and L. Huifeng, Principle And Evaluation Method Of Active Lightning Arrester, Shanghai 200030, China: Dept. of Electric Engineering, 2002.

[31] T. Allcutt, "Lightning Arrester Spark Gaps Their Relation to the Problem of Protecting Against," *in Presented at the 34th A nnual Convention of the American Institute of Electrical Engineers*, Atlantic City, 1918.

[32] R. Shariatinasab, B. Vahidi, S. H. Hosseinian and M. Sedighizadeh "Selection of Station Surge Arresters Based on the Evaluation of Failure Probability Using Artificial Neural Networks," in Dept. of Elec. Eng. , Amirkabir Univ. of Technology, Tehran, Iran, 2017.

[33] G. W. Walsh, "A Review of Lightning Protection and Grounding Practice," *IEEE Transactions on Industry Applications*, Vols. Vol.IA-9, no. No. 2, March/April 1973.

[34] E. Chikuni, F. Engelbrecht, O. I. Okoro and M. Dondo, "The Emergence of Substation Automation in Southern Africa, Opportunities, Challenges and Threats," *in International Conference on Power System Technology*, 2010.

[35] A. R. Hileman, Insulation Coordination., New York: Marcel Dekker, 1999.

[36] M. A. Ismaili, P. Bernard, R. Lambert and A. Xémard, "Estimating the probability of failure of equipment as a result of direct lightning strikes on transmission lines," IEEE Trans. Power Delivery, vol. Vol. 14, p. 1394–1400, Oct. 1999.

[37] F. Fernandez and R. Diu, "Metal oxide surge arrester model Cor fast transient simulations," *in Intemational conference on power system transients*, June 2001..

[38] C. A. Christodoulou, V. Vita, G. Perantzakis, L. Ekonomou and G. Milushev, "Adjusting the Parameters of Metal Oxide Gapless Surge Arresters' Equivalent Circuits Using the Harmony Search Method," 18 December 2017.

[39] G. R. Lira, D. Fernandes and E. G. Costa, "Parameter identification technique for a dynamic metal-oxide surge arrester model In Proceedings of the," *in International Conference on Power Systems Transients (IPST2009)*, Kyoto, Japan, 2–6 June 2009.

[40] T. Zhao and Q. Li, "Investigation on Digital Algorithm for On-Line Monitoring and Diagnostics of Metal Oxide Surge Arrester Based on anAccurate Model*," IEEE Transactions on Power Delivery*, vol. Vol. 20, no. No.2,, April 2005.

[41] H. J. Li, S. Birlasekaran and S. S. Choi, "A Parameter Identification Technique for Metal-Oxide Surge Arrester Models," *IEEE Transactions On Power Delivery*, vol. Vol. 17, no. No.3, July 2002.

[42] K. Munukutla, V. Vittal, G. T. Heydt, D. Chipman and B. Keel, "Transmission Line Arrester Energy, Cost, and Risk of for Transmission Line Lightning Protection," *IEEE Transactions On Power Delivery*, Vol. 25, no. NO. 3, pp. 1742-1780, July 2010.

[43] F. Castro-Aranda,, "Lightning performance of over head," *IEEE Trans. Power Del*, vol. Vol. 20, no. No. 3, pp. 2200-2210, July, 2005.

[44] H. Dehbonei, "The Challenges of Sub-optimal Substation Site Selection," *in IEEE*, Perth, Australia, 2016.

[45] E. Chikuni, F. Engelbrecht, I. O. Okoro and M. Dondo, "The Emergence of Substation Automation in Southern Africa, Opportunities, Challenges and Threats," *in International Conference on Power System Technology*, 2010.

[46] M. Naedele, D. Dzung and M. Stanimirov, "Network Security for Substation Automation Systems," *in Proceedings of the 20th International Conference on Computer Safety, Reliability and Security*, September 26-28, 2001.

[47] J. Cai, Y. Zheng and Z. Zhou, "Review of Cyber-Security Challenges and Measures in Smart Substation," *in International Conference on Smart Grid and Clean Energy Technologies, Beijing*, China, 2016.

[48] C. Christodoulou, M. Avgerinos, L. Ekonomou, I. Gonos and I. Stathopulos, "Measurement of the resistive leakage current in surge arresters under artificial rain test and impulse voltage subjection", *IET Sci. Meas. Technol. J.*, vol. 3, no. 3, pp. 256-262, 2009.

[49] S. Shirakawa, F. Endo, H. Kitajima, S. Kobayashi, K. Goto and M. Sakai, "Maintenance of surge arrester by a porTable arrester leakage current detector", *IEEE Trans. Power Deliv.*, Vol. 3, no. 3, pp. 998-1003, 1998.

[50] J. B. Lee, I. K. Song, J. Y. Kim, B. S. Lee and T. H. Kwon, "Aging characteristics of polymer lightning arrester by multi-stress accelerated aging test," *Proceedings of the 2004 IEEE International Conference on Solid Dielectrics*, Toulouse, France, vol.1, pp. 371-374, 2004.

[51] S. Das, R. Ghosh, S. Dalai and B. Chatterjee, "Study on the effect of moisture ingression into metal oxide surge arrester using leakage current analysis," *3rd International Conference on Condition Assessment Techniques in Electrical Systems* Rupnagar, 2017, pp. 330-334, 2017

[52] M. Li, X.S. Han, M. Yang and Z.H. Guo, "Basic concept and study theory of condition-based maintenance for power transmission system", *Proceedings of the CSEE*, vol. 31, no. 34, pp. 43-52, 2011.

[53] J. Heo, M. Kim, G. Park, Y. Yoon, J. Park, S. Lee "A reliability-centered approach to an optimal maintenance strategy in transmission systems using a genetic algorithm", *IEEE Transactions on Power Delivery*, vol. 26, no. 4, pp. 2171-2179, 2011.

[54] G. Levition and A. Lisnianski, "Optimization of imperfect preventive maintenance for multi-state systems", *Reliability Engineering and System Safety*, vol. 67, pp. 193-203, 2000.

[55] H. Heo, M. Kim, G. Park, Y. Yoon, J. Park, S. Lee "A reliability-centered approach to an optimal maintenance strategy in transmission systems using a genetic algorithm", *IEEE Transactions on Power Delivery*, vol. 26, no. 4, pp. 2171-2179, 2011

[56] J. Endrenyi and G. J. Anders, "Aging maintenance and reliability", *IEEE Power Energy Mag.*, vol. 4, no. 3, pp. 59-67, May-Jun. 2006.

[57] P. Tuethong, P. Yutthagowith and S. Maneerot, "Design and construction of a variable air-core inductor for lightning impulse current test on surge arresters," *33rd International Conference on Lightning Protection (ICLP)*, Estoril, pp. 1-4, 2016.

[58] N. Triruttanapiruk, M. Leelajindakrairerk and P. Yutthagowith, "Surge arrester parameter estimation from experimental result", *Asia -Pacific International Conference on Lightning Korea*, pp. 67-70, June 2013.

[59] C. Xingang, T. Xiaoxiao and F. Li, "Research of Infrared Diagnosed of Faults of Arrester," *International Conference on High Voltage Engineering and Application*, Chongqing, pp. 637-640, 2008.

[60] Li Da-peng, Sun Feng-rui. "Diagnostic Availability Research of Infrared Fault Diagnosis of Machine and Electric Device" *Mechanical and Electrical Equipment*, Vol. 21 no. 7 pp45-48, July 2004.

[61] Li Gui-lian. "Study on Infra-Red Photo Analysing System and the Standard for Diagnosing MOA", *Hubei Power*, Vol. 25 No. 2 pp. 38-39, March 2001.

[62] H. de Oliveira, M. Martinez, I. Campos, R. de Oliveira, C. de Salles and C. Lefort, "New Techniques for Field Inspection of Medium Voltage Surge Arresters," 2007 *IEEE Lausanne Power Tech*, Lausanne, 2007, pp. 39-44, 2007.

[63] D. da Silva, E. da Costa, J. De Franco, M. de Jesus, S. Abreu, Kari Lahti and Lucia Helena, "Degradation by immersion test versus electrical performance*", International Journal of Electrical Power & Energy Systems,* Vol. 53, pp. 488-498. May 2013.

[64] R. Barradas, G. Rocha J. Muniz, U. Bezerra, M. Nunes, J. Silva "Methodology for analysis of electric distribution network criticality due to direct lightning discharges". *Energies*, vol. 13 April 2020.

[65] M.A. Araújo, R.A. Flauzino, R.A.C. Altafim, Oureste E. Batista, Lucas A. Moraes, "Practical methodology for modelling and simulation of a lightning protection system

using metal-oxide surge arresters for distribution lines" *Electric Power Systems Research,* Vol. 118, pp. 47-54, Jan. 2015.

[66] B. Franc, B. Filipović-Grčić, V. Milardić, "Lightning overvoltage performance of 110kV air-insulated substation" *Electric Power Systems Research*, Vol. 138, pp. 78-84, 2016.

[67] P. Yang, S. Chen and J. He, "Lightning Impulse Corona Characteristic of 1000-kV UHV Transmission Lines and Its Influences on Lightning Overvoltage Analysis Results," *IEEE Transactions on Power Delivery*, Vol. 28, no. 4, pp. 2518-2525, Oct. 2013.

[68] T. Zhang, L. Sun and Y. Zhang, "Study on Switching Overvoltage in Off-Shore Wind Farms," *IEEE Transactions on Applied Superconductivity*, Vol. 24, no. 5, pp. 1-5, Oct. 2014.

[69] J. A. Martinez, D. Goldsworthy and R. Horton, "Switching Overvoltage Measurements and Simulations—Part I: Field Test Overvoltage Measurements," *IEEE Transactions on Power Delivery*, Vol. 29, no. 6, pp. 2502-2509, Dec. 2014.

[70] T. Tsuboi, J. Takami, S. Okabe, K. Inami and K. Aono, "Weibull parameter of oil-immersed transformer to evaluate insulation reliability on temporary overvoltage," *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 17, no. 6, pp. 1863-1868, Dec. 2010.

[71] A. Akinrinde A. Swanson, I. Davidson, "Investigation and Mitigation of Temporary Overvoltage Caused by De-Energization on an Offshore Wind Farm" *Energies* Vol. 13, Aug. 2020.

[72] M. Tuczek, M. Bröker, V. Hinrichsen and R. Göhler, "Effects of Continuous Operating Voltage Stress and AC Energy Injection on Current Sharing Among Parallel-Connected Metal–Oxide Resistor Columns in Arrester Banks," *IEEE Transactions on Power Delivery*, Vol. 30, no. 3, pp. 1331-1337, June 2015.

[73] A. Kalyuzhny, "Analysis of Temporary Overvoltage During Open-Phase Faults in Distribution Networks with Resonant Grounding," *IEEE Transactions on Power Delivery*, Vol. 30, no. 1, pp. 420-427, Feb. 2015.

[74] H. Ghoddami and A. Yazdani, "A Mitigation Strategy for Temporary Overvoltage Caused by Grid-Connected Photovoltaic Systems," *IEEE Transactions on Energy Conversion,* Vol. 30, no. 2, pp. 413-420, June 2015.

[75] M. Ropp, M. Johnson, D. Schutz and S. Cozine, "Effective grounding of distributed generation inverters may not mitigate transient and temporary overvoltage", *Proc. Western Protective Relay Conf.*, pp. 1-8, 16–18, Oct. 2012.

[76] M. Calado and S. Mariano, "Determination of the Earth Fault Factor in Power Systems for Different Earthed Neutrals*," IEEE Latin America Transactions*, Vol. 8, no. 6, pp. 637-645, Dec. 2010.

[77] V. Hinrichsen, G. Scholl, M. Schubert and T. Ostertag, "on Line Monitoring of High Voltage Metal-oxide Surge Arrester by wireless Passive Surface Acoustic Wave (SAW) Temperature Sensors. Int. Symposium on HV Eng. London 1999 paper 2.238.

[78] DHT11 Digital Temperature and Humidity Sensor Module User Manual v1.0 Harbin Aosong Robot Technology Co. Ltd. 2010.10

[79] H. Wang and W. Gao, "Research on Application of Fuzzy Decoupling Algorithm in Temperature and Humidity Control," in Computing Technology and Automation, China, 2018, Vol.37, pp.31-34.

[80] Y. Zhong, "Design of Temperature and Humidity Measurement and Control System of Intelligent Showcase," M.S. China. Hefei University of Technology, 2016

[81] X. Zhao, J. Tang and D. Chen, "Research of Temperature and Humidity Decoupling Control for Central Air-conditioning System," *International Conference on Intelligent Human-Machine Systems and Cybernetics (Proceeding of the IEEE)*, Yinchuan, China, 2013, pp.1381-1385.

[82] U. Taira: Save-Energy Type Temperature Humidity Simultaneous Control using Model Predictive Control Method, *Journal of SICE*, 43-9, 686/690, 2004.

[83] H. Elahi, M. Sublich, M.E. Anderson and B.D. Nelson, "Lightning Overvoltage Protection of the Paddock 362-145 kV Gas-insulated Substation," in IEEE Transaction on Power Delivery, Vol.5, no.1, pp.144-150, Jan 1990.

[84] K.L. Chrzan, "Influence of moisture and partial discharges on the degradation of high-voltage surge arresters", *Euro. Trans. Electrical Power*, vol. 14, 2004.

[85] K. Shreyas, S. Reddy., " Multi stress ageing Studies on Polymeric Housed Surge Arresters", *Electronics Computing and Communication Technologies (CONECCT) 2020 IEEE International Conference on*, pp. 1-4, 2020.

[86] K. Lahti, K. Kannus and K. Nousiainen, "Behaviour of the DC Leakage Currents of Polymeric Metal Oxide Surge Arresters in Water Penetration Tests", *IEEE Transactions on Power Delivery*, vol. 13, no. 2, April 1998.

[87] M. Marwala and P. Bokoro, "Assessing the impact of field intensity on the performance reliability of varistor arresters", *AFRICON 2019 IEEE*, pp. 1-4, 2019.

[88] P. Bokoro, W. Doorsamy, "Mapping Reliability Predictors of Low-Voltage Metal Oxide Surge Arresters Using Contour Plots", Access IEEE, vol. 8, pp. 164497-164503, 2020.

[89] D. K. Mohammad and Z. Raqab. “Estimation of for three-parameter Weibull distribution”, Statistics *& Probability Letters,* vol. 79, pp. 1839-1846, Sept. 2015.

[90] P. Wais, “Two and three-parameter Weibull distribution in available wind power analysis”, *Renewable Energy,* vol. 103, pp. 15-29, 2017.

[91] Y.M. Kantar and B. Şenoğlu, “A comparative study for the location and scale parameters of the Weibull distribution with given shape parameter”, *Computers & Geosciences,* vol.34 no. 12, pp. 1900 – 1909, April 2008.

[92] E.J. Green, F.A. Roesch, A.F. Smith, and W.E. Strawderman. "Bayesian Estimation for the Three-Parameter Weibull Distribution with Tree Diameter Data." *Biometrics* 50, no. 1 pp. 254-69, 1994

[93] M. Savic, "Estimation of the Surge Arrester Outage Rate Caused by Lightning Overvoltage," *IEEE Transactions on Power Delivery,* vol. Vol.20, no.1, Jan. 2005.

[94] I. Gonos, L. Ekonomou, F. Topalis, I. Stathopulos, "Probability of back flashover in transmission lines due to lightning strokes using Monte-Carlo simulation," *International Journal of Electrical Power and Energy Systems,* pp. 107–111, 2003.

[95] M. Hori, M. Nishioka, Y. Ikeda, K. Noguchi, K. Kajimura and H. Motoyama, "Internal winding failure due to resonance overvoltage in distribution transformer caused by winter lightning," *IEEE Transactions on Power Delivery*, vol. 21, no. 3, pp. 1600-1606, July 2006.

[96] T. Wakai, N. Itamoto, T. Sakai and M. Ishii, "Evaluation of transmission line arresters against winter lightning," *IEEE Transactions on Power Delivery*, vol. 15, no. 2, pp. 684-690, April 2000.

[97] J. Tarchini, and W. Gimenez, "Line surge arrester selection to improve lightning performance of transmission lines,"*IEEE Bologna PowerTech Conference*, Bologna, Italy, 2003.

[98] P. Pinceti and M. Giannettoni, "A simplified model for zinc oxide surge arresters*,"* *IEEE Transactions on Power Delivery* vol. 14, pp. 393-398, 1999.

[99] I. W. G. 3.4.11, "Modeling of metal oxide surge arresters," *IEEE Transactions on Power Delivery*, pp. 320-309, 1992.

[100] A. Carvalho, M. Lacorte and O. Knudsen, "Improved EHV line switching surge control by application of MO-arresters and controlled switching," *Proceedings 1995 International Conference on Energy Management and Power Delivery EMPD*, Singapore, vol.1, pp. 292-297, 1995.

[101] C. Heinrich and V. Hinrichsen, "Diagnostics and monitoring of metal-oxide surge arresters in high-voltage networks-comparison of existing and newly developed procedures," *IEEE Transactions on Power Delivery*, vol. 16, no. 1, pp. 138-143, Jan. 2001.

[102] I. Metwally, M. Eladawy and E. Feilat, "Online condition monitoring of surge arresters based on third-harmonic analysis of leakage current," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 24, no. 4, pp. 2274-2281, 2017.